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EVALUATION OF SOLAR PHOTOVOLTAIC ENERGY STORAGE FOR AIDS TO NAV--ETC(U)
NOV 80 W R ALLEN, J S RYBA, S E TRENCHARD
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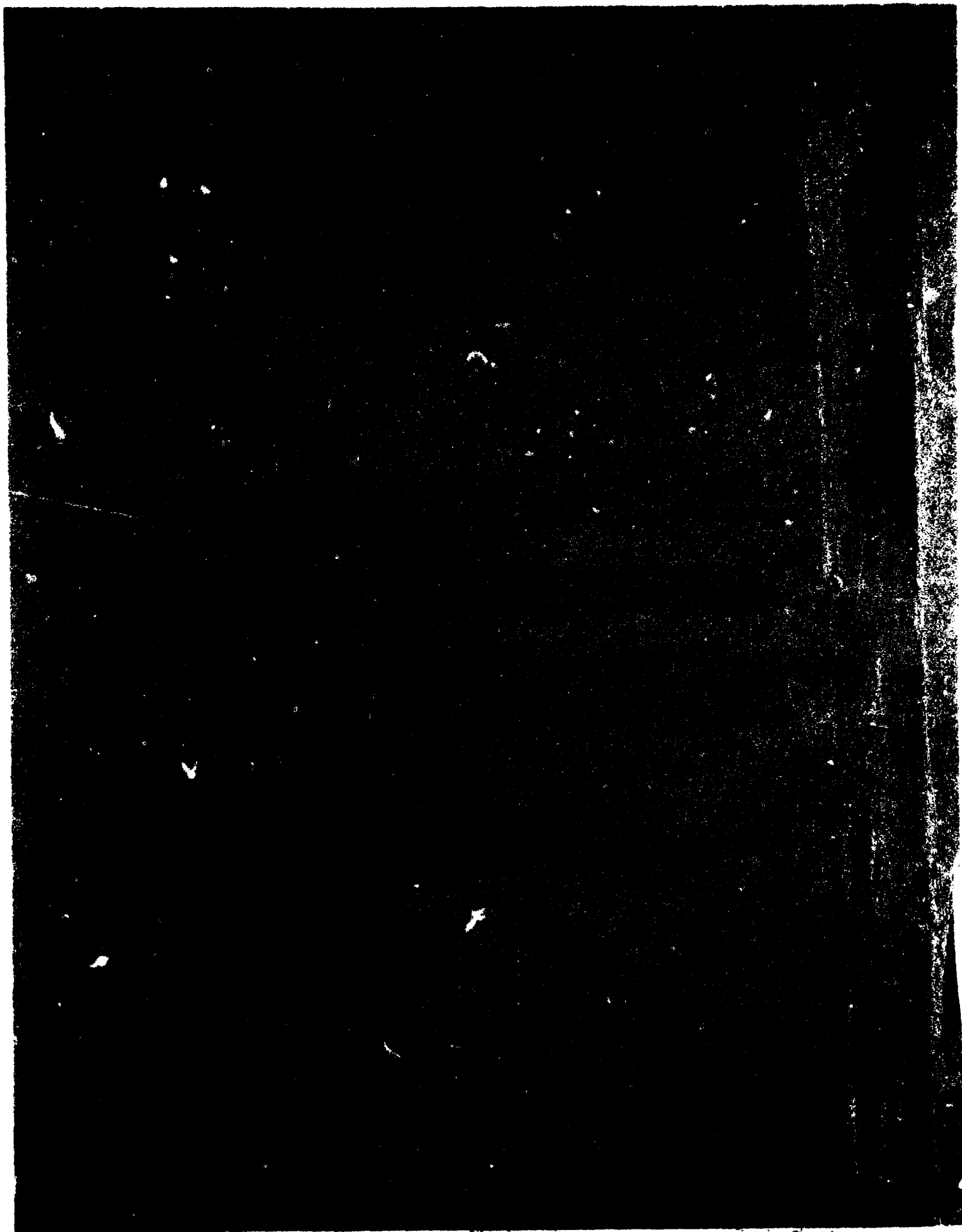
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16. Abstract <p>A detailed discussion of the U.S. Coast Guard aids to navigation application of solar photovoltaics with an emphasis on energy storage by lead-acid batteries is presented. A methodology is developed for the prediction of performance of a lead-acid battery in low-rate photovoltaic charging. Experimental results from five years of solar photovoltaic charging of lead-antimony grid batteries at various levels of voltage regulation are discussed. A two-level, two-factorial experiment with pure-lead grid batteries is analyzed. An experimental comparison is made between pure-lead grid and lead-calcium grid batteries. The results of temperature-controlled zener diode voltage regulator testing are presented.</p> <p>All three grid types of lead-acid batteries were found to be acceptable for aids to navigation usage with different constraints on voltage regulation and maintenance needed for each type.</p> <p>A final discussion is presented on the considerations for the operational deployment of solar photovoltaic-powered aids to navigation.</p>		
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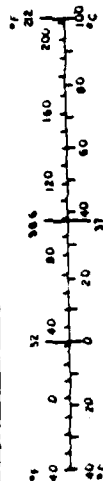
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
sq ft	square inches	6.5	square centimeters	cm ²
sq yd	square feet	0.09	square meters	m ²
sq mi	square yards	0.8	square meters	m ²
	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsip	teaspoons	5	milliliters	ml
fl oz	tablespoons	15	milliliters	ml
c	fluid ounces	30	milliliters	ml
pt	cups	0.24	liters	l
qt	pints	0.47	liters	l
gal	quarts	0.96	liters	l
cu ft	gallons	3.8	liters	l
yd ³	cubic feet	0.03	cubic meters	m ³
	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
ha	hectares (10,000 m ²)	0.4	square miles	mi ²
	hectares (10,000 m ²)	2.6	acres	ac
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	sh
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
	liters	1.06	quarts	qt
	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
yd ³	cubic yards	1.3	cubic feet	ft ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (after add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

Batteries serve as the power source for nearly all of the over 14,000 lighted aids to navigation maintained by the United States Coast Guard. For nearly 20 years, primary batteries (i.e., non-rechargeable) of the zinc-carbon air-depolarized type have been successfully used for aids to navigation service. Maintenance and replacement schedules are well established and the batteries are highly reliable. Notwithstanding, these batteries are becoming less attractive due to rising replacement costs, restricted availability, and increasing disposal difficulties caused by environmental concerns.

Solar energy is the leading alternative natural power source and the heart of virtually every solar photovoltaic energy system in existence is a secondary battery (i.e., rechargeable). For about seven years, the U.S. Coast Guard Research and Development Center has been actively studying secondary batteries in solar photovoltaic energy applications; these efforts are discussed in the present report. For the purposes of this report, the complete battery research program can be conveniently divided into three distinct but overlapping test phases: exploratory testing, voltage regulation testing, and life expectancy testing.

Exploratory testing began in early 1974 as a part of research efforts directed at solar photovoltaic energy systems. In all, 53 separate systems were placed in operation, each consisting of a solar array, a lead-acid storage battery, flashing light, and, in some cases, a voltage regulator. The basic purpose was to evaluate the particular components and to ascertain the system reliability in aids to navigation operation. Preliminary results indicated several areas where information was incomplete or totally lacking; thus, the scope of inquiry was broadened.

Using the experience gained from the exploratory phase as a guide, plus other research, a new phase of investigation began with more definitive methods. Voltage regulation testing was initiated during August and September 1975 using 15 new photovoltaic systems assembled from usable components no longer needed in the then still operating exploratory phase systems, plus new components chosen on the basis of experience and research. Three groups of five identical systems using arrays with predictable outputs and operating at three different levels of voltage regulation were placed in operation. These systems provided data on the suitability of zener diodes as voltage regulators and the optimum regulation point, and provided a means to further investigate water usage in liquid electrolyte batteries.

During this phase it became evident that there was a need for data to predict the life expectancy of batteries in solar power applications. Accordingly, life expectancy testing was begun in the summer of 1978 using a standard two-level factorial experimental design as the fundamental method. Voltage regulation and battery discharge depth were the independent variables used for measuring the effects on battery life. This design also permitted an attempt at establishing the relationship between regulating voltage and water usage.

The major results emanating from the exploratory phase have been reported earlier.⁽¹⁾ This report includes the results of voltage regulation and life expectancy testing. It also extends the earlier report by including information from the exploratory testing which was not available when the first report was written.

The results of research efforts to date permit the conclusion that it is technically feasible to use solar photovoltaic systems in both lighted buoys and lighted fixed aids. The problems associated with these applications have been well researched in the laboratory in addition to several operational demonstrations.⁽²⁾ The economics of such systems are attractive.⁽³⁾ The results appearing in this report are also supportive of the operational deployment of solar photovoltaic energy systems. No technical problems have been identified which preclude a high level of confidence in their effectiveness and reliability.

2.0 BACKGROUND

2.1 Historical Perspective

The first buoy powered by electricity was positioned in New York Harbor in 1888. The source, a cable from shore, did not prove reliable. About 1910, acetylene gas lights for buoys were brought into general usage. Battery-powered lights started being used about 1935 but it was 1968 before the last acetylene-lighted aid in the U.S. was retired. Large secondary lead-acid storage batteries were used, requiring removal to shore depots for periodic recharging and redeployment. In 1962, the shift from secondary batteries to primary batteries began with the principal economic justifications being the elimination of battery-charging shops at shore depots and reduced handling problems.

The life span for the zinc-air primary batteries presently being used varies due to many factors, but on the average, it is about two years, with a maximum life of three years due to shelf-life considerations.

Besides its basic non-biodegradability, a depleted zinc-air primary battery has certain components that can have detrimental effects on the marine environment. These batteries contain a highly alkaline solution of pH 14. They also contain mercury, a long-term pollutant, which is present in the zinc anodes and the byproduct residue. Accordingly, primary batteries cannot be disposed of on-site nor can they be disposed of by deep ocean dumping. Depleted batteries must be returned to shore depots for subsequent shore site disposal with direct or indirect use of sanitary landfill being the most widely used method of disposal. Although direct costs are now low and not readily identifiable, it is obvious that present disposal methods are becoming less desirable. If present methods are curtailed or halted due to depleted landfills or more restrictive local, state, or federal environmental regulations, the direct cost to the government may well become prohibitive.

Considerations such as these prompted the Coast Guard to initiate several research thrusts during the past decade in alternative low-power energy sources for aids to navigation. Research efforts focused on wind-and wave-activated generators, fuel cells, and solar photovoltaic energy systems. Of these, the solar photovoltaic system held the most promise for widespread deployment.

2.1.1 Solar Power

The Coast Guard Field Testing and Development Center at Curtis Bay, Maryland (predecessor of the Research and Development Center) conducted limited testing with solar cells in the 1960s; however, those efforts were terminated because of the high costs and poor reliability associated with the solar cells of that period. By 1971, advances in silicon solar arrays brought about by the space program suggested that solar power now had significant potential as a new power source for aids to navigation.

Accordingly, proposals for solar-powered systems were sought by Coast Guard Headquarters. Two proposals were received, with each being substantially different in component sizing for the same requirements. The large difference in the designs resulted from an incomplete knowledge of the

magnitude of the variables that would affect system operations, and from the selection of different safety factors by the companies. These proposed systems were procured and the companies were given contracts to test the systems at their own plants. To obtain more knowledge, the decision was made to acquire additional systems and operate them in Coast Guard facilities. For this purpose, 34 solar-powered systems were ordered from each company in the spring of 1972. Each system consisted of a solar array, a storage battery, and a box to house the battery, and required wiring and any other components, such as voltage regulators, that might be added.

In the fall of 1972, the Coast Guard Research and Development Center was established at Groton, Connecticut. In one of its first assignments, the Center was directed to evaluate the solar-powered systems that had been acquired. The goal appeared simple: determine whether these systems would operate satisfactorily for a number of years. It was soon apparent that things were more complicated than initially thought. The real need was to find out if solar energy systems were cost-effective substitutes for the primary batteries being used. To do this, it was necessary to know how to optimize system design and what the most probable causes of failure would be. A "laboratory evaluation" could help reach that goal by research into actual long-term operation of solar-powered systems, by the testing of various components in a real-world environment, by the evaluation of various modifications to the components, and by the development of an optimum system design. Thus, a program was conceived to operate the system in as near a real-world environment as possible and to critically observe, measure, and document all performance parameters. During 1973, details of the program were finalized, test instrumentation was procured, facilities were designed and constructed, and late in the year the systems to be evaluated were received. In the spring of 1974, 53 systems were placed in operation and exploratory testing was begun.

3.0 EVALUATION OF BATTERY TYPES FOR AIDS TO NAVIGATION APPLICATIONS

In order to select a battery type for a photovoltaic energy system, it is necessary to define the battery's role in a photovoltaic energy system.

3.1 Photovoltaic Energy System

A typical solar photovoltaic energy system for powering lighted aids to navigation is shown in figure 3-1. The secondary battery provides a source of power and acts as a buffer between a properly sized photovoltaic cell array and the load. The blocking diode prevents current drain from the battery through the photovoltaic cell array at night. The voltage regulator, when included in the system, prevents overcharging the battery. Presence or absence of a voltage regulator is determined by the electrical operating characteristics of the battery (this point will be discussed more completely later in the report). Each of the system components in the aids to navigation application will be described.

3.1.1 Electrical Load

The electrical load illustrated in figure 3-1 consists of a flasher and a lamp assembly. The flasher is a solid-state, power conditioning, electronic switch which applies power to the lamp in a predetermined manner controlling both flash duration and flash sequence. The flasher incorporates a day-night "switch" which initiates lamp operation during periods of darkness. The standard U.S. Coast Guard flasher operates at a nominal input voltage of 12 volts.

Table 3-1 lists typical flasher dissipation in ampere-hours per day for standard Coast Guard flashers. These figures are based upon flasher operation at 60°F and assumes 13 hours of operation per day.

<u>Flash Characteristics</u>	<u>Duty Cycle</u>	<u>Flash Duration (SEC)</u>	<u>Flasher Dissipation (Amp-Hr Per Day)</u>
FL6 (0.6)	0.10	0.6	0.222
FL4 (0.4)	0.10	0.4	0.222
FL2.5 (0.3)	0.12	0.3	0.228
GPFL5 (2x.4)	0.16	0.4	0.238
IQKFL (6x.3)	0.18	0.3	0.243
FL4 (1.0)	0.25	1.0	0.261
MO(A) (0.4, 2.0)	0.30	0.4, 2.0	0.274
QKFL (0.3)	0.30	0.3	0.274
QPFL6 (2x1.0)	0.33	1.0	0.284
EI6 (3.0)	0.50	3.0	0.326
OCC4 (3.0)	0.75	3.0	0.391
FIXED	1.00	---	0.456

Table 3-1
Duty Cycle, Flash Duration Time, and Flasher Dissipation
for Standard Coast Guard Flashers

The flasher dissipation current is a load that acts in addition to the load when the lamp is radiating. Table 3-2 provides the

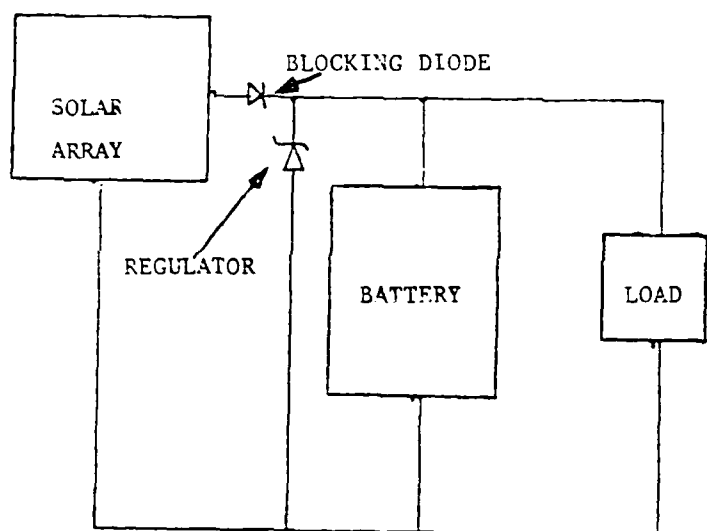


FIGURE 3-1
GENERAL CONFIGURATION OF SOLAR PHOTOVOLTAIC ENERGY SYSTEMS

average lamp current for various flash duration corrected for cold filament turn-ons.

Nominal Lamp Rating (Amps)	Flash Duration (SEC)						
	0.3	0.4	0.5	0.6	1.0	2.0	3.0
0.25	0.278	0.271	0.268	0.266	0.258	0.254	0.252
0.55	0.639	0.621	0.605	0.596	0.578	0.564	0.559
0.77	0.916	0.894	0.870	0.859	0.816	0.793	0.785
1.15	1.420	1.380	1.330	1.310	1.240	1.200	1.180
2.03	2.760	2.620	2.500	2.450	2.230	2.130	2.100
3.05	-----	4.150	3.910	3.810	3.420	3.240	3.170

Table 3-2
Average Current Corrected for Cold Filament Surge Current
for Various Flash Durations

Although the electrical load may vary from aid to aid due to the use of different lamps and flash sequences, the great majority of aids require less than 2 watts of average power. The most widely used Coast Guard aid employs a 0.55 ampere lamp with FL4 (0.4) flash characteristic. Utilizing tables 3-1 and 3-2, the daily battery discharge for this lamp and flasher is determined as follows:

Average lamp current	0.621 amperes
Flasher duty cycle	x.10
Hours darkness (average)	x 13 hours/day
	= 0.808 amp-hrs/day
Flasher dissipation	+ .222
Battery discharge	= 1.030 amp-hrs/day

The battery discharge may be calculated for actual periods of darkness by use of the American Ephemeris or Nautical Almanac.

3.1.2 Solar Cell Array

The solar cell array to be used in aids to navigation will typically consist of a planar array of 33 solar cells connected in series. The array will have an open circuit voltage of approximately 18 volts under direct sun. When illuminated, the array will supply current to charge the battery. The electrical characteristics for a typical solar array are illustrated in figure 3-2.

The electrical response of the array varies with changes in illumination intensity or solar incidence angle. Figure 3-3 provides typical cell current-voltage characteristics as a function of solar incidence angle at constant cell temperature. The short circuit current drops approximately as the cosine of the incident angle. Departures from cosine law dependence are primarily due to surface reflections which are most pronounced at grazing incidence angles. Since the array of cells is usually conservatively loaded (in the range of 0.35 to 0.40 volts per series cell) in order to accommodate temperature effects, the current output from an array will tend to follow a cosine law response to changes in solar incidence angle. Additional contributions to electrical output are produced by illumination enhancement resulting from sky radiation, reflections from clouds, etc.

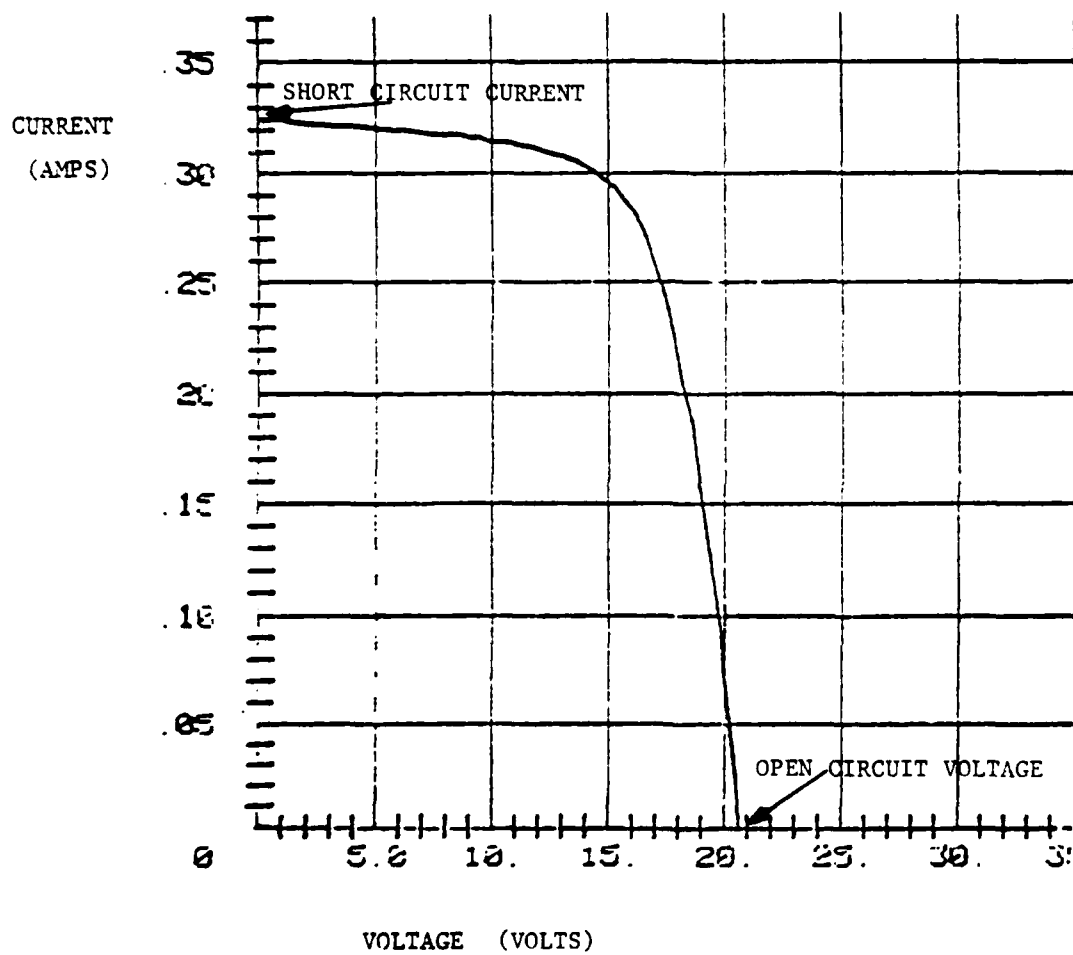


FIGURE 3-2
ELECTRICAL CHARACTERISTIC OF A TYPICAL SOLAR ARRAY FOR
A LIGHTED AID TO NAVIGATION AT 25°C

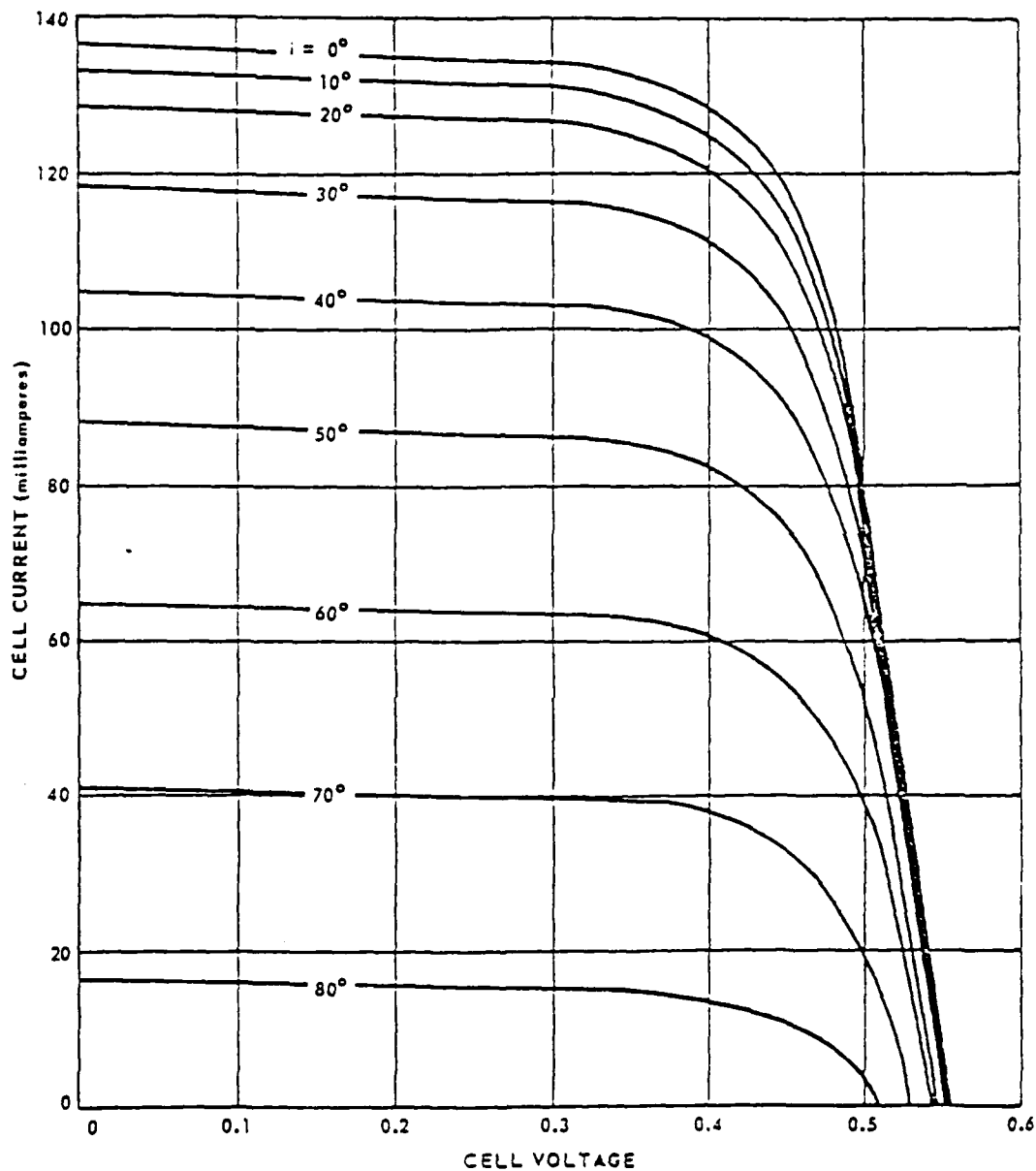


FIGURE 3-3

SOLAR CELL ELECTRICAL CHARACTERISTICS AS A FUNCTION OF
SOLAR INCIDENCE ANGLE, CELL TEMPERATURE 25°C

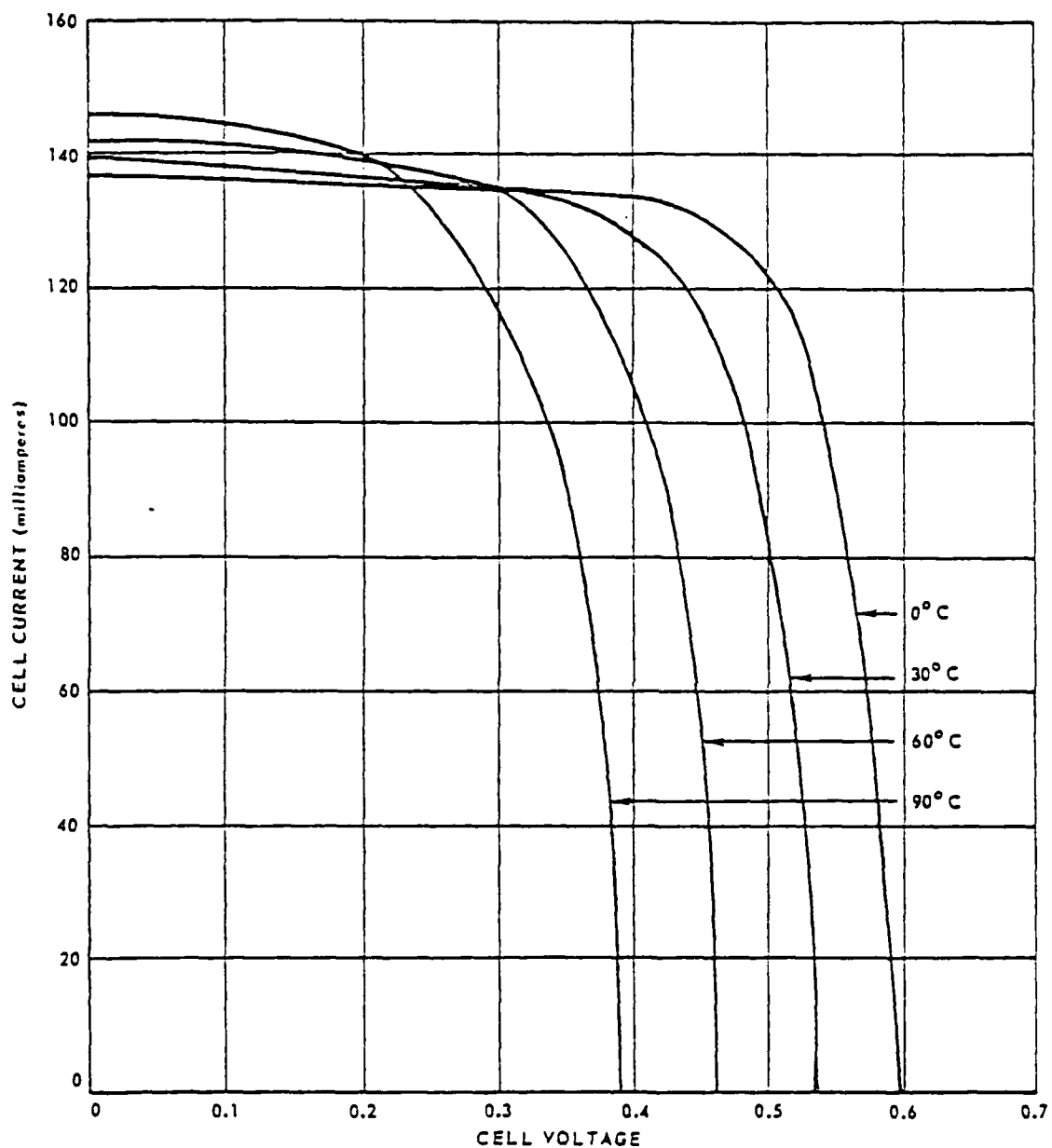


FIGURE 3-4
TEMPERATURE EFFECT ON ELECTRICAL CHARACTERISTICS FOR
A 2x2 CM, 10 OHM-CM SOLAR CELL AT 100 mW/CM² ILLUMINATION

The magnitude of the temperature effects are illustrated in figure 3-4. At higher operating temperatures, open circuit voltage decreases at approximately $-2.2 \text{ mV/cell/}^{\circ}\text{C}$. Short circuit current is not significantly affected by the operating temperature of the array.

3.1.3 Charge Regulator

The photovoltaic energy system may incorporate a charge regulator for the explicit purpose of controlling battery charge and/or overcharge. This is needed in the charging of most secondary batteries to minimize water loss and gas evolution while enhancing lifetime in terms of charge-discharge cycles. Charge regulators and charge regulation will be discussed at length in subsequent chapters.

3.1.4 Battery

The battery used in the photovoltaic energy system is a rechargeable battery which acts as a reservoir of energy to operate the aid during periods of darkness. During the daylight hours the array either fully or partially recharges the battery depending upon the availability of solar energy. There are two distinct cyclic demands placed on the battery. One is relatively "shallow" but highly repetitive charge-discharge with a frequency of one cycle per day. The second discharge cycle is a long-term gradual deep discharge on a one cycle per year basis (as illustrated in figure 3-5).

3.2 Evaluation of Candidate Batteries

Under contract, the Naval Weapons Support Center at Crane, Indiana, developed a comprehensive list of secondary battery types for possible use in aids to navigation using system information and battery requirements supplied by the Coast Guard. The potential of various battery types was determined from discussions with battery users, experts, test reports, industry representatives, and supplemental data, including manufacturers' performance characteristics. The list derived is shown in Table 3-3. (Appendix A summarizes the salient advantages and disadvantages of each battery type examined by the Naval Weapons Support Center using their data plus information obtained by the R&DC from discussions with manufacturers, manufacturers' performance data, and experimental results.)

3.3 Selection of Battery for Aids to Navigation

The survey of candidate batteries identified two types of batteries that would be acceptable: nickel-cadmium and lead acid. When compared in terms of operating characteristics such as self-discharge rate, operating temperature, operating voltage, efficiency, maintenance needs, and cycle life, neither battery was clearly superior in a majority of these areas. (Appendix B gives a full listing of characteristics affecting secondary batteries in aids to navigation usage.) The final decision was made on the basis of cost and the lead-acid was clearly less expensive.⁽⁴⁾

The nickel-cadmium is superior to lead acid in expected life and cold weather performance which could make its usage in extremely remote, cold applications cost effective. The most notable drawbacks of nickel-cadmium are high cost, high self-discharge, and low charge storage efficiency at low charging rates.

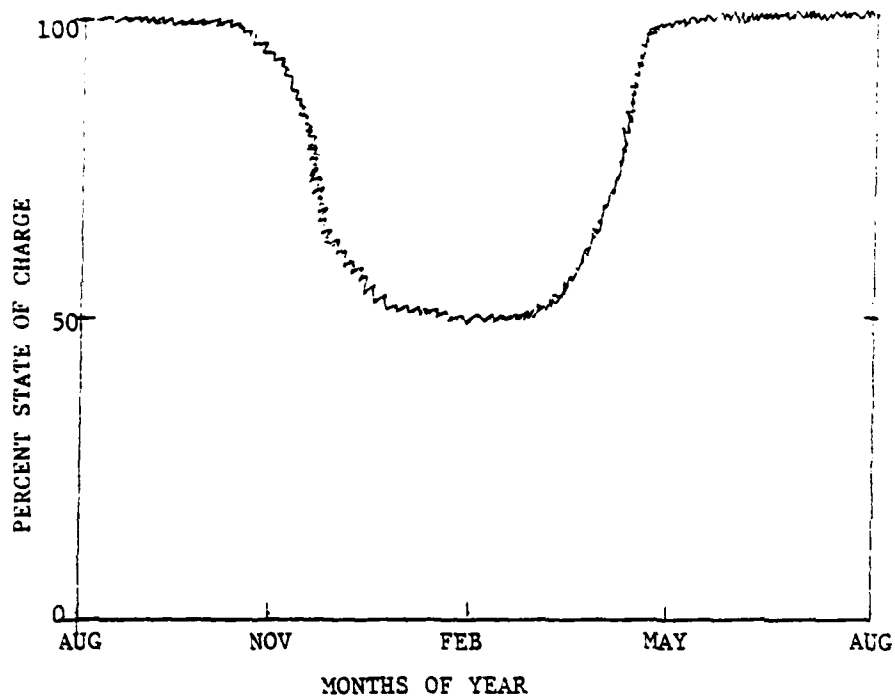


FIGURE 3-5
YEARLY STATE OF CHARGE PROFILE FOR A BATTERY IN
SOLAR PHOTOVOLTAIC AIDS TO NAVIGATION USAGE

TABLE 3-3
LIST OF BATTERIES CONSIDERED

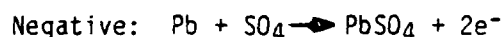
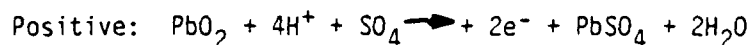
1. Alkaline-Manganese Dioxide
2. Cadmium-Air
3. Lead-Acid (Antimony Alloy Grid)
4. Lead-Acid (Calcium Alloy Grid/Sealed)
5. Lead-Acid (Calcium Alloy Grid/Vented)
6. Lead-Acid (Gelled Electrolyte)
7. Lead-Acid (Pure Lead Grid/Charge Retaining)
8. Lithium-Sulfur
9. Nickel-Cadmium (Pocket Cell/Vented or Sealed)
10. Nickel-Cadmium (Sealed)
11. Nickel-Cadmium (Sintered Plate Cells/Vented)
12. Nickel-Hydrogen
13. Nickel-Iron Alkaline
14. Nickel-Zinc (Vented or Sealed)
15. Silver-Hydrogen
16. Silver Oxide-Cadmium Alkaline (Vented)
17. Silver Oxide-Zinc Alkaline (Vented)
18. Sodium-Sulfur
19. Zinc-Air
20. Zinc-Oxygen

4.0 LEAD-ACID STORAGE BATTERIES

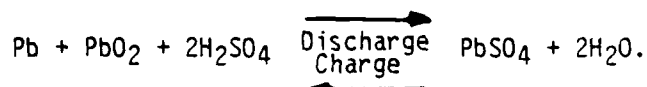
The lead-acid storage battery is the most widely used electrochemical system of the many that are commercially available. These batteries have been available for over 100 years and have received both widespread and large-scale use for over 75 years. They offer the user a significant cost advantage when compared with other secondary battery types, due in large measure to large volume production. A complete discussion of lead-acid storage batteries is not appropriate for the purposes of this report; however, a comprehensive overview is presented to aid in understanding their operating characteristics as applied to aids to navigation usage.

4.1 Fundamental Operation(5)

Lead-acid cells consist of positive and negative electrodes immersed in an electrolyte solution of dilute sulfuric acid. When the cell is fully charged, the active material of the positive electrode is lead dioxide (PbO_2), and of the negative electrode, lead (Pb). As the cell is discharged, both electrodes are quantitatively converted to lead sulfate as follows:



Overall, the combined reaction, known as the double-sulfate theory, is to convert lead dioxide and sulfuric acid to lead sulfate and water:



During the process, the electrodes remain solid because lead, lead dioxide, and lead sulfate are all relatively insoluble in sulfuric acid. The reactions are reversible, and the cell may be recharged to its initial state.

The active materials are either applied as a cemented paste to a lattice grid or electrochemically to a highly developed surface used to enhance surface area. In some cells small amounts of antimony, along with traces of arsenic and other materials, are often alloyed with the grid lead to strengthen the grids, facilitate grid casting, and increase cell life. In applications where low self-discharge and/or low gassing rates are important, lead-calcium alloys, or pure lead grids are sometimes used. The length, width, and thickness of the plates in a cell are determined by the required capacity of the cell. The positive and negative plates are separated by porous sheet forms of wood, rubber, glass, or plastic. The resultant sandwich assembly of plates and separators are physically constrained in a container of rubber or plastic (sometimes referred to as a jar) holding the sulphuric acid electrolyte.

4.2 Specific Gravity of the Electrolyte⁽⁶⁾

It is standard practice to indicate electrolyte acid concentration in terms of specific gravity. Table 4-1 presents some of the characteristics of sulfuric acid electrolyte solutions in the range of specific gravities typically used in lead-acid storage batteries.

The data presented in table 4-1 are based on solutions at 59°F (15°C). Since the measured specific gravity of an electrolyte is dependent on the temperature of the solution, a compensating correction must be made. Equivalent specific gravity for a given solution temperature may be calculated from the data in table 4-1, using the following equation:

$$SG = SG_{59} + c(59 - T)$$

Where:

SG = specific gravity at temperature T
SG₅₉ = specific gravity at 59°F (15°C)
c = temperature coefficient per °F
T = temperature of the solution in °F

It should be noted that the temperature coefficient, c, is a function of the specific gravity at 59°F (15°C). The specific gravity of a cell is highest when the cell is fully charged.

Sulfuric acid is consumed during discharge so that the specific gravity of the electrolyte becomes increasingly lower as the discharge proceeds. Specific gravities for fully charged batteries range from about 1.200 to about 1.300, depending on battery type and ambient temperature conditions.

The freezing temperature of the electrolyte increases with decreasing specific gravity, as seen in table 4-1. Figure 4-1 presents the freezing point of sulfuric acid as a function of specific gravity. Freezing of the electrolyte within a lead-acid cell can result in permanent plate damage and reduced cell life. It is, therefore, important that the specific gravity of the electrolyte be maintained at a level high enough to prevent freezing, especially during the coincident periods of deep discharge and cold ambient conditions which would exist in solar photovoltaic systems during winter months in more northern latitudes. To provide protection against freezing, it is generally necessary to oversize a system commensurate with the minimum anticipated operating temperature.

Knowledge of specific gravity also conveys other important information. Since the specific gravity of the electrolyte varies with state-of-charge, it is possible to deduce a cell's present state-of-charge and depth-of-charge by measuring specific gravity.

During charging, both hydrogen and oxygen gasses are evolved from the cell, particularly near 100 percent state-of-charge. This gassing removes water from the electrolyte, lowering its level in the battery and raising the specific gravity. The specific gravity must be corrected for electrolyte level prior to a determination of state-of-charge.

TABLE 4-1
PROPERTIES OF SULFURIC ACID SOLUTIONS

SPECIFIC ⁽¹⁾ GRAVITY	TEMPERATURE COEFFICIENT		H ₂ SO ₄ PERCENT CONCENTRATION		FREEZING POINT	
	PER °F	PER °C	WEIGHT	VOLUME	°F	°C
1.000	-	-	0.0	0.0	32	0
1.010	0.00010	0.00018	1.4	0.8		
1.020	12	22	2.9	1.6		
1.030	14	26	4.4	2.5		
1.040	16	29	5.9	3.3		
1.050	18	33	7.3	4.2	26	-3.3
1.060	20	36	8.7	5.0		
1.070	22	40	10.1	5.9		
1.080	24	43	11.5	6.7		
1.090	26	46	12.9	7.6		
1.100	27	48	14.3	8.5	18	-7.8
1.110	28	51	15.7	9.5		
1.120	29	53	17.0	10.3		
1.130	31	55	18.3	11.2		
1.140	32	58	19.6	12.1		
1.150	33	60	20.9	13.0	5	-15
1.160	34	62	22.1	13.9		
1.170	35	63	23.4	14.9		
1.180	36	65	24.7	15.8		
1.190	37	66	25.9	16.7		
1.200	38	68	27.2	17.7	-17	-27
1.210	38	69	28.4	18.7		
1.220	39	70	29.6	19.6		
1.230	39	71	30.8	20.6		
1.240	40	72	32.0	21.6		
1.250	40	72	33.2	22.6	-61	-52
1.260	40	73	34.4	23.6		
1.270	41	73	35.6	24.6		
1.280	41	74	36.8	25.6		
1.290	41	74	38.0	26.6		
1.300	42	75	39.1	27.6	-95	-71
1.310	42	75	40.3	28.7		
1.320	42	76	41.4	29.7		
1.330	42	76	42.5	30.7		
1.340	42	76	43.6	31.8		
1.350	43	77	44.7	32.8	-56	-49

⁽¹⁾At 59°F (15°C)

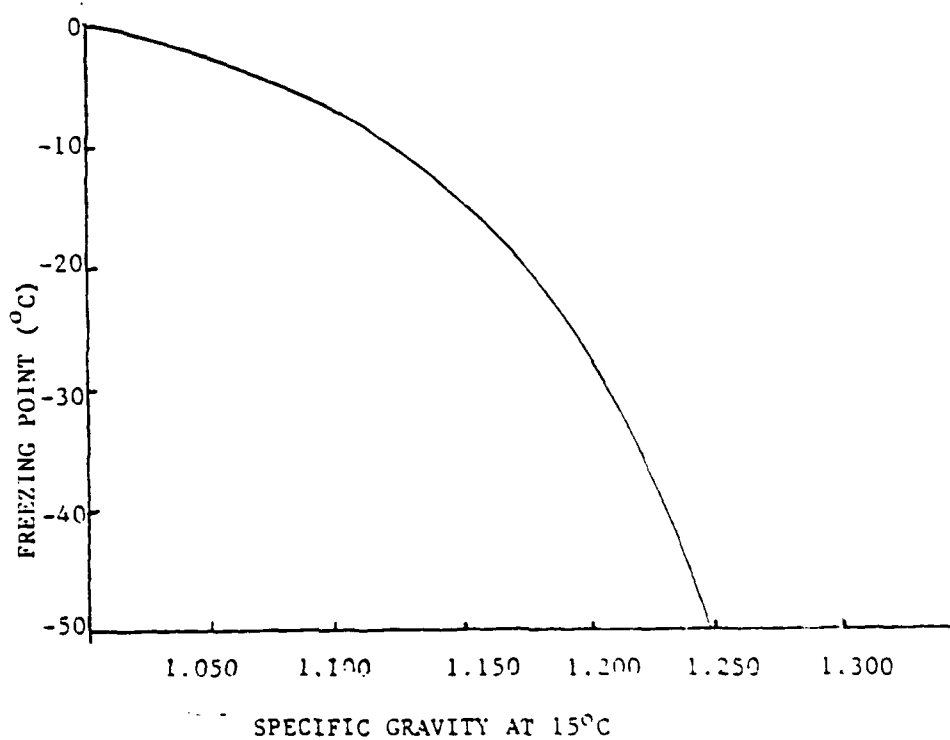


FIGURE 4-1
FREEZING POINT OF SULFURIC ACID ELECTROLYTE AS A FUNCTION OF SPECIFIC GRAVITY

4.3 Sulfation(7)

Crystals of lead sulfate form at both the positive and negative plates of lead-acid batteries due to the discharge reaction. Technically, the overall process is known as sulfation, and it occurs in three characteristic ways: (1) fine sulfate crystals form as a natural part of the discharge process, (2) sulfate forms as a result of localized action or self-discharge of the plates (due to parasitic currents or acid action on the plate materials), and (3) large crystals or crusts of sulfate form as a result of neglect or misuse. The term sulfation is most commonly used to describe this last process. The effects of the first two processes are easily reduced by the charging current and are not sources of trouble. The last process, known as "Ostwald Ripening," can result in both temporary and permanent damage to the plates.(8)

Excessive sulfation of the third kind is difficult to reduce. It comes from (1) allowing the battery to stand in a discharged condition for a considerable time, (2) operating the battery for prolonged periods of time at partial states of charge, (3) neglecting to make repairs when evidence of trouble within the cells becomes apparent, (4) filling the cells with electrolyte when water should have been used, (5) operating the battery at excessive temperatures, and (6) persistent undercharging. The aids to navigation application with the prolonged periods of operation in a partially discharged state (see figure 3-5) runs the risk of sulfation. Prolonged operation in the summer near 100% state-of-charge tends to counter this risk. Experience at the R&D Center has shown that the positive plate grid thickness is critical to controlling sulfation effects (section 5.4).

4.4 Operating Voltage Characteristics(9)

The terminal voltage of a lead-acid cell is a function of charge rate, discharge rate, state-of-charge, cell temperature, specific gravity of the electrolyte and, to some extent, cell construction and previous history.

On discharge, the cell voltage decreases with increasing discharge rate and decreasing state-of-charge. Figure 4-2 presents typical curves for cell terminal voltage as a function of depth-of-discharge for various discharge rates at constant operating temperatures. For relatively low discharge rates voltage falls rather gradually at first until finally a point is reached where further discharge results in a rapid voltage reduction. This point is referred to as the knee of the voltage curve and occurs at higher states-of-charge for increasing discharge rate. Manufacturers usually specify a discharge cutoff voltage just past the knee. This is done because little additional energy can be withdrawn from the cell beyond this point and because further discharge can result in permanent damage.

The cell terminal voltage of a lead-acid cell is affected by the operating temperature of the cell. Figure 4-3 presents cell voltage as a function of depth-of-discharge at various temperatures, for a constant rate of discharge. The battery charge rate or discharge rate is usually described as a fraction of the nominal name plate capacity "C" (i.e., 0.07C charge rate for a 100 ampere-hour battery denotes a charge current of 0.07×100 , or 7.0 amperes). The curves are based on a table of lead-acid charge capacity versus discharge rate and temperature data fitted to the Sheperd model.(10) As can

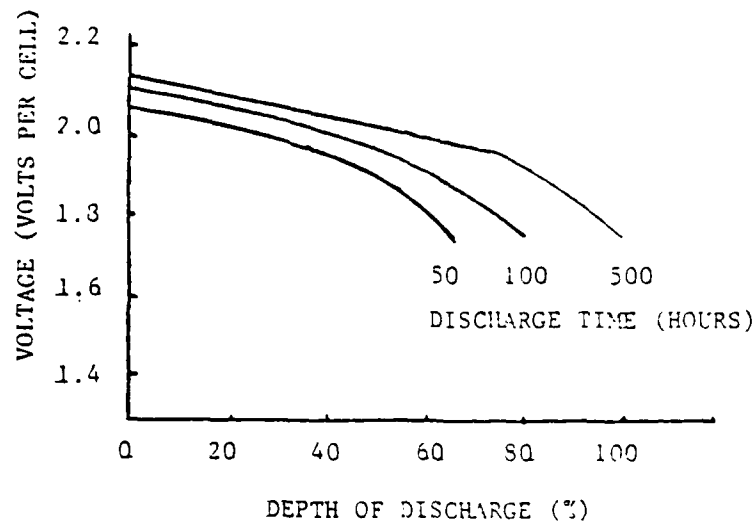


FIGURE 4-2

LEAD-ACID LOW RATE PHOTOVOLTAIC BATTERY DISCHARGE VOLTAGE

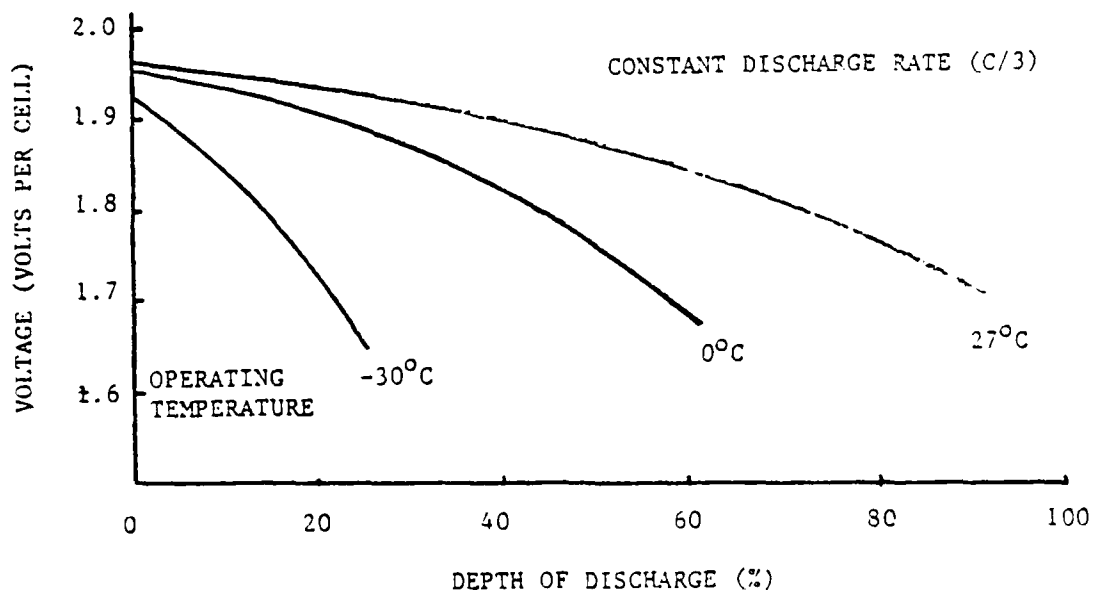


FIGURE 4-3

LEAD-ACID BATTERY DISCHARGE VOLTAGE AS A FUNCTION OF TEMPERATURE

be seen in figure 4-3. at a given depth-of-discharge, voltage decreases with decreasing temperature, especially as depth-of-discharge increases. The effect of temperature on available capacity is discussed in section 4.5.2.

On discharge, the cell terminal voltage, for a specified rate, temperature, depth-of-discharge and electrolyte specific gravity, can also be reduced by the effects of sulfation. However, these effects are not well quantified at the present time.

Voltage characteristics on charging exhibit similar dependence on operating parameters such as rate, state-of-charge, temperature and previous cell history. These characteristics are discussed further in section 4.6.

4.5 Capacity⁽¹¹⁾

Lead-acid batteries are commonly rated in terms of their ampere-hour (Ah) capacity. Rated capacity is given for a specified discharge rate at a specified operating temperature and cutoff voltage. For example, a cell might be rated 200 Ah at the 8-hour rate for an operating temperature of 77°F. This means that the cell will deliver 25 amperes for 8 hours before reaching the specified cutoff voltage. The removal of 200 Ah from the cell is equivalent to a 100% depth of discharge.

Available capacity is variable, and for the aids to navigation application is a function of discharge rate, operating temperature, self-discharge rate, age, and sulfation.

4.5.1 Discharge Rate

The available capacity is significantly affected by the discharge rate. In general, a lead-acid battery, all things being equal, will deliver higher capacity at lower discharge rates (and conversely, lower capacity at higher discharge rates). Experience at the Coast Guard R&D Center has shown a 20% increase in capacity above the rated 8-hour discharge capacity for batteries operating at the low charge and discharge rates of aids to navigation applications.

4.5.2 Operating Temperature

The available capacity of a lead-acid cell discharged at a specified rate to a specified cutoff voltage decreases with decreasing temperature. One percent per degree centigrade is a typical value for the temperature coefficient of capacity of a lead-acid battery.⁽¹²⁾ Temperatures above 77°F (25°C) tend to increase capacity slightly. In the aids to navigation application, this reduction in capacity at low temperatures has not been a significant factor. At the lowest temperatures of operation expected, the maximum amount of energy removed in a daily cycle is only 3% of capacity.

4.5.3 Self-Discharge Rate

Self-discharge is a phenomenon caused by parasitic electrochemical reactions taking place within a charged cell, reducing its stored energy with an increase in time. Originally, self-discharge was considered to be an additional external load on the system which would have to be balanced

by increasing the generating capacity of the array. Experience with high self-discharge and low self-discharge batteries operating in solar photovoltaic aids to navigation indicates that self-discharge is not a significant load factor. There are two possible explanations:

1. Self-discharge is associated with a battery operating in a no-load situation. In aids to navigation usage the battery is rarely in a no-load situation. During the daylight hours, it is receiving charge from the solar panel. During the night hours, it is constantly under load from the flasher dissipation current (section 3.1.1) and receives additional loading when the lamp radiates.

2. In general, the rate of self-discharge increases with increasing temperature. Figure 4-4 presents a typical range of self-discharge rates as a function of cell temperature for cells containing antimony and calcium grids. In the aids to navigation application, when the battery is at a low state-of-charge, the outside temperature is low (i.e., winter) and the self-discharge rate is low. When the temperature rises (i.e., summer), the self-discharge rate rises but battery state-of-charge is high due to increased insolation on the panel. In both cases, the reduction in capacity from self-discharge is minimized.

4.5.4 Age

The capacity of a lead-acid cell varies during its lifetime. The exact shape of the capacity versus life curve and the actual lifetime are dependent of the type of cell and its operating history. Increases in capacity during the first few cycles are a manifestation of initially incomplete grid formation.

4.5.5 Sulfation

The available capacity of a lead-acid cell can also be reduced by the effects of sulfation, which causes a reduction in the discharge voltage that results in attainment of the cutoff voltage at a higher state-of-charge than for an unsulfated cell.

4.6 Charging(13)

Proper charging conditions are essential to achieve acceptable charge efficiencies and maximum life for lead-acid batteries. Charging at too high a rate, or significantly after 100 percent state-of-charge is reached, results in a sharp voltage rise within the cell. This voltage rise causes production of hydrogen and oxygen (called gassing), which has several detrimental effects. Gassing also creates turbulence within the cell which, although desirable to prevent stratification of the electrolyte, can dislodge active material from the plates. Excessive gassing can therefore result in decreased cell life. Escaping hydrogen and oxygen can constitute an explosion hazard, and also necessitate addition of water to keep the plates completely immersed and maintain proper electrolyte concentration. Excessive charge rates and/or overcharge can also result in increased cell temperatures, which tend to accelerate grid corrosion and other destructive mechanisms within the cell.

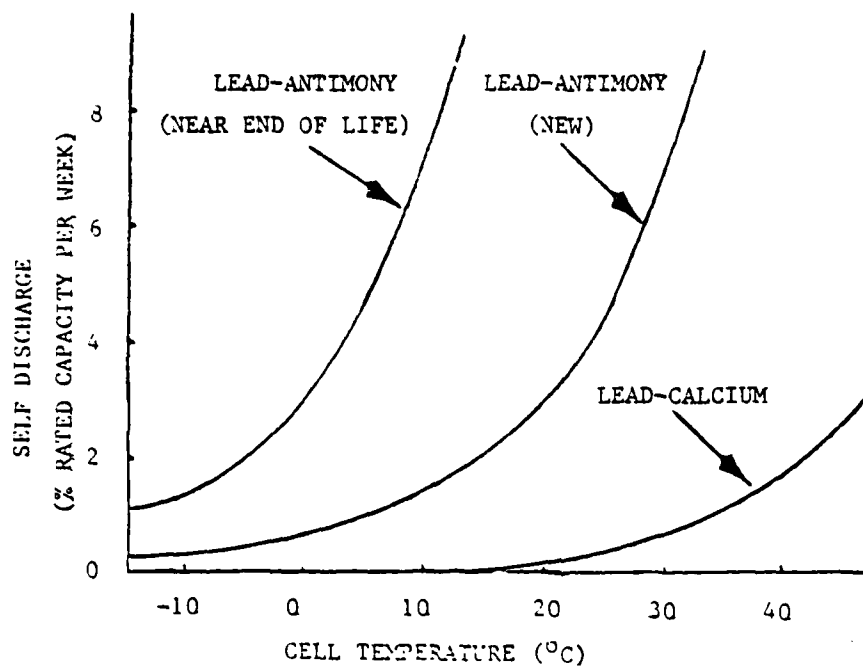


FIGURE 4-4

LEAD-ACID BATTERY SELF-DISCHARGE RATE AS A FUNCTION OF TEMPERATURE

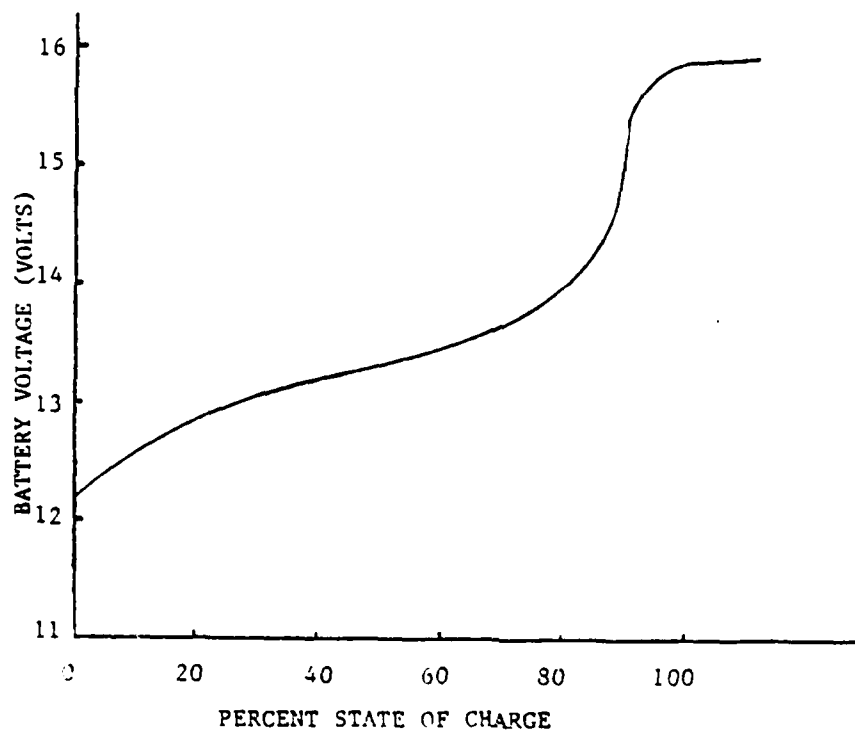


FIGURE 4-5

TYPICAL LEAD-ACID BATTERY CHARGING VOLTAGE AT
0.07C CHARGE RATE AND ROOM TEMPERATURE

A typical voltage characteristic of a 6-cell lead-acid battery under charge is provided in figure 4-5. The terminal voltage rises slowly in monotonic fashion as the battery is recharged. As full charge is approached, the terminal voltage tends to rise markedly until equilibrium is achieved in overcharge. This voltage rise is somewhat dependent upon the rate of charge and is less pronounced at lower rates.

As the charge progresses, the specific gravity of the electrolyte rises. Depending upon the type of battery and the ambient temperature, the specific gravity at full charge will range between 1.2 and 1.3. Most liquid electrolyte types recommended for photovoltaic applications use a relatively high specific gravity in order to afford additional protection against freezing.

Near the end of charge and during overcharge gasses are evolved within the lead-acid battery; the gases liberated are oxygen at the positive plate and hydrogen at the negative plate. Gassing begins when the terminal voltage is above 2.2 volts per cell. The amount of gassing and the percent composition of hydrogen and oxygen liberated are a function of voltage and, to some extent, cell construction.

Gassing can impact rather significantly upon the requirements for battery water addition; water loss due to hydrolysis, aggravated by evaporation and carried off in vented gases, can make maintenance requirements rather costly. Some gassing is considered desirable to prevent electrolyte stratification in flooded cells. This may have merit in the recharge of a battery in a stationary shore aid but it is obviously a dubious requirement in a buoy system where wave action would provide ample agitation of battery electrolyte. Excessive gassing can loosen active materials in pasted plates, particularly the positives.⁽¹⁴⁾ This tends to limit the useful lifetime of the battery. Since the battery in a solar-powered aid will spend considerable time in overcharge during the summer months when elevated temperatures aggravate water loss, it is essential to control gassing by limiting the current to the battery when it is fully charged.

4.7 Efficiency⁽¹⁵⁾

The overall, or round trip, energy efficiency of a lead-acid battery is approximately determined by the product of the ampere-hour and voltage efficiencies. These are dependent on both cell design and operating conditions.

Ampere-hour efficiency (electro-chemical efficiency) is the ratio of the ampere-hours' output to the ampere-hours of the recharge. This can also be called storage efficiency. In photovoltaic systems knowledge of this efficiency is essential in predicting how much of the solar array output is stored for later use. Information compiled at the R&DC indicates that the charge storage efficiency for aids to navigation photovoltaic systems is on the order of 98-99%. Figure 4-6 shows the relationship derived from this information for the full range of battery state-of-charge.⁽¹⁶⁾

Voltage efficiency is the ratio of the average voltage during the discharge to the average voltage during the recharge. Voltage efficiency is determined by the charge and discharge rates, and by the operating temperature

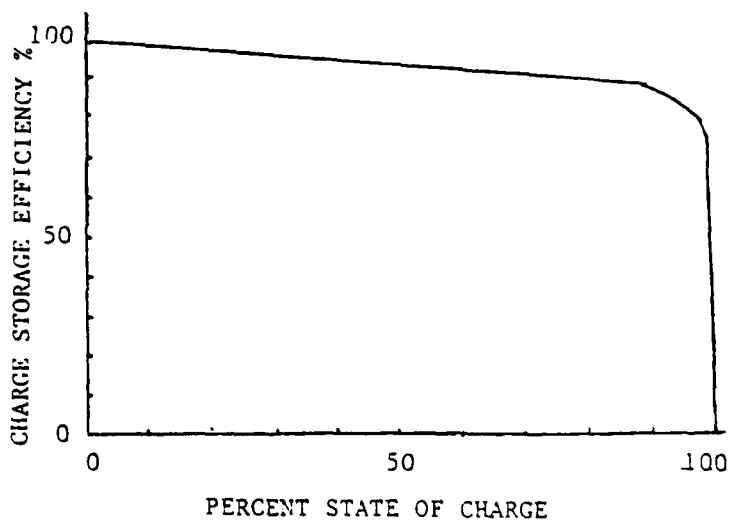


FIGURE 4-6

BATTERY AMPERE-HOUR STORAGE EFFICIENCY FOR
PHOTOVOLTAIC CHARGING AT RATES LESS THAN C/100

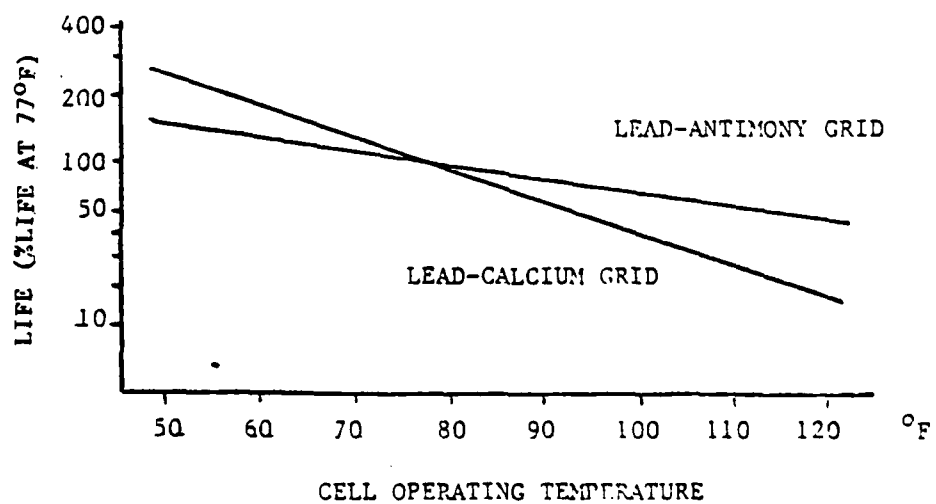


FIGURE 4-7

EFFECT OF TEMPERATURE ON LEAD-ACID BATTERY LIFE

of the battery. High rates and low temperatures both act to reduce voltage efficiency.

Inefficiencies within the lead-acid cell result in heat generation during operation. The heat evolved from the cell has two components: an irreversible (I_R) component and a reversible (heat of reaction) component.⁽¹⁷⁾ The reversible heat is positive (exothermic) on charging and (endothermic) negative on discharging, while the irreversible heat is always positive. Therefore, the two heat components are in opposition during discharge and in tandem during charge. This results in greater temperature rises during charge, as opposed to discharge, at a given rate. The rate of heat generation and cell temperature rise are dependent on charge or discharge rate, state-of-charge, specific characteristics of cell/battery design and ambient conditions. The very high efficiencies noted in our application indicate that the magnitude of heat generation and temperature rise during photovoltaic operation is very small.

4.8 Life⁽¹⁸⁾

The capacity of a lead-acid cell remains relatively constant over the majority of its useful lifetime, but eventually begins to fall off rapidly. End-of-life is usually defined as the point when the available capacity falls to 80 percent of rated capacity when the cell was new.

Table 4-2 presents typical lifetimes in terms of charge-discharge cycles for the various types of lead-acid batteries presently available.

TABLE 4-2
LEAD-ACID BATTERY LIFE

Cell Type	Grid Type	Life	
		Years	Cycles ⁽¹⁾
Automotive	Lead-antimony	2-5	150-250
Automotive	Lead-calcium	2-5	20-50
Motive power	Lead-antimony	5-15	1000-2000
Motive power	Lead-calcium	10-20	750-1500
Stationary	Lead-antimony	15	250-500
Stationary	Lead-calcium	15-24	100-500
Stationary	Plante	4-30	250-500
Photovoltaic	Lead-calcium	10-20	350
Photovoltaic	Pure lead	5-15	--
Sealed	Lead-calcium	2-5	100-200

(1) To 89 percent depth of discharge at 77°F.

Operation of lead-acid cells at elevated temperatures accelerates destructive mechanisms within the cell (due to increased chemical activity) and reduces cell life. Figure 4-7 illustrates the effect of operating temperature on cell life. Cell life can also be reduced in cells that are sulfated, excessively overcharged, or by physical damage to the plates.

4.8.1 Cycle Life

In a photovoltaic power system for an aid to navigation there are two distinct cyclic demands imposed upon the battery: the first is a relatively "shallow" but highly repetitive charge-discharge with a frequency of one cycle per day, while the second is a long-term gradual deep discharge on a one-cycle-per-year seasonal basis (illustrated in figure 3-5).

Evidence indicates an approximately linear relationship between the logarithm of the number of cycles to failure and the average depth of discharge to which a cell is subjected.⁽¹⁹⁾ It must be remembered, however, that battery lifetime is also limited by a maximum calendar life regardless of depth of discharge or number of cycles.

4.9 Cost

The lead-acid battery offers a significant cost advantage over other types; relatively low cost of materials, coupled with high volume production to meet an evergrowing market has made the lead-acid battery the most inexpensive secondary battery available today.⁽²⁰⁾

Lead-acid battery costs vary, depending on the type of cell and, to some extent, cell size. Table 4-3 presents typical battery costs, in dollars per kilowatt-hour for the various types of cells presently available. The costs were obtained in mid-1979 and represent only the cost of the cell and electrolyte, unless otherwise indicated. The range of costs shown for each cell type results from cost variations that occur as a function of cell size (ampere-hour capacity) and from differences between manufacturers.

TABLE 4-3
TYPICAL LEAD-ACID BATTERY COSTS

<u>Cell Type</u>	<u>Grid Type</u>	<u>Battery Cost - \$/kWh⁽¹⁾⁽²⁾</u>
Automotive	Lead-antimony	70
Automotive	Lead-calcium	70-77
Diesel starting	Lead-calcium	142-162
Motive power	Lead-antimony	112-130
Motive power	Lead-calcium	150-200 ⁽³⁾
Stationary	Lead-antimony	112-130
Stationary	Lead-calcium	122-130
Stationary	Plante	365
Low rate photovoltaic	Lead-calcium	135-175 ⁽³⁾
Low rate photovoltaic	Pure lead	98
Medium rate photovoltaic	Lead-calcium	165-225 ⁽³⁾
Sealed	Lead-calcium	375

(1) Range results from cost variations that occur as a function of cell size (ampere-hour capacity) and from differences between manufacturers

(2) Cost of lead at \$0.60/lb

(3) Includes battery trays and cell interconnects

Costs presented in table 4-3 are based on lead at \$0.60 per pound. Lead-acid battery costs will naturally be affected by the general inflation rate, as well as by fluctuations in the price of lead. For example, a typical motive power cell will contain on the order of 70 pounds of lead per kilowatt-hour of rated capacity. Therefore, each \$0.01/lb change in the price of lead will result in a \$0.50 to \$1.00/kWh change in battery cost.

5.0 EXPLORATORY TESTING

As mentioned in section 1.0, the Coast Guard began a formal, exploratory testing program in early 1974. A total of 53 systems, generally configured as shown in figure 1-1, were installed on a rooftop facility at Groton, Connecticut. The location, adjacent to Long Island Sound, served as a simulation of the marine environment. Eighteen systems had voltage regulation, evenly split between shunt and series configurations. (For a specific description of the various systems as well as a high level of detailed information on all components of the systems the reader is referred to the Ryba and Naus report of June, 1976, previously referenced. The present report will focus only on batteries and will bring the exploratory testing up to date.) The batteries used are described in table 5-1.

TABLE 5-1

DESCRIPTION OF BATTERIES USED IN EXPLORATORY TESTING

Manufacturer:	Gates	Gates	Globe	Globe	Wisco	Wisco
Manufacturer Designation:	(Special Purchase)	(Special Purchase)	GC12200 Type A	GC12200 Type A	DA-2-1	DD-3-3
Voltage:	12	12	12	12	12	12
Capacity (Ah):	30	60	40	60	26	100
Grid Construction	Pure lead	Pure lead	Lead-Calcium	Lead-Calcium	Pure lead	Pure lead
Electrolyte	Liquid contained in porous separator material	Liquid contained in porous separator material	Jellied	Jellied	Liquid	Liquid
Number Installed:	9	12	10	4	6	12

Although there were expectations of at least a six-year life for system components at the on-set of exploratory testing, only two of the original systems are operating today, six years later. Twenty-five batteries were lost during the first two years of operation because the solar arrays associated with them failed. The six 26Ah Wisco batteries were found to be unsuitable for the intended application because of high water usage and were removed from the test during the second year. Of the batteries in systems that did not fail outright, only three batteries survived two years with a capacity of 80% or better (the generally accepted minimum capacity before declaring battery failure). Two of these batteries were 100Ah Wisco batteries and one, a 40Ah Globe battery. These same two 100Ah Wisco batteries are still in operation today. The Globe failed in its third year.

5.1 Voltage Regulation

Since it is possible for typical solar arrays to generate voltages in excess of battery full charge voltages, some form of regulation is necessary. Indeed, all battery manufacturers recommend maximum charging voltages to prevent over-charge of their batteries. The need for regulation is further increased by the variability of the operating conditions of a battery in solar photovoltaic system service. These variable conditions include changing local insolation levels, dirt accumulation, aging, manufacturing variations, and temperature variations.

In order to explore some of the ramifications of voltage regulation in solar photovoltaic systems, each of the two array manufacturers supplied nine systems with voltage regulators of their choice. One supplied non-adjustable, series type regulators; the other, adjustable shunt type. A program of voltage regulator measurements was not initiated since it was felt that their design and manufacture was so state-of-the-art that no problems would be encountered. This proved to be an incorrect assumption. Daily summaries indicated that some batteries were not receiving the expected array output. This was traced to the adjustable voltage regulators that had drifted to lower than original settings. After several readjustments during the first few months, it was decided to stop making adjustments, measure the voltage periodically, and observe the effect of any drift on the systems.

Although the differences in water usage between regulated and unregulated systems was marked for one type of liquid electrolyte battery, the variance in voltage from the regulators combined with poorly performing arrays made evaluation of voltage regulator effectiveness very difficult. These results in conjunction with the early failure of some systems led to the initiation of new tests focusing more carefully on voltage regulation. (The methods and results of this new phase of inquiry will be discussed more fully in section 6.0.) A comprehensive study of voltage regulators accomplished in the summer of 1975 indicated a simple one-element voltage regulator such as a zener diode regulator was a likely candidate.⁽²¹⁾ Accordingly, a total of fifteen new systems were placed in service during August and September 1975 to test the effectiveness of zener diodes as voltage regulators. There were five identical systems at each of the following levels of regulation: 13.8V+5%, 13.1V+5%, and unregulated. All systems used two 6V, 100Ah Mule lead-acid batteries (Model 6MLG-11), with lead-antimony plates and liquid electrolyte, under identical loads. Water usage was the dependent variable examined as a measure of voltage regulation effectiveness.

It would seem obvious that limiting the amount of overcharge will reduce the amount of water used by a battery and, if not limited to the point of undercharging, this should increase the battery life. However, picking the optimum point at which to regulate a battery is made difficult because of the trade-offs involved. Lower voltages mean less overcharge, lower water use and less grid corrosion, but with lower voltage limits more energy that could go into the battery gets dissipated in the regulator. This causes the battery to recharge at slower rates and dip to greater depths of discharge (DOD) than when regulated at higher voltages. Battery current-voltage (I-V) curves give a better picture of the problem.

5.2 Battery I-V Curves

Battery I-V curves describe the current voltage relationships of a battery at a particular state of charge. Examples are shown in figures 5-1, 5-2, and 5-3. Originally prepared for use in the computer modeling of a solar photovoltaic system, they were found to be very useful in analyzing effects observed in real systems.⁽²²⁾

In order to generate the battery I-V curves, new batteries were chosen. Each was cycled to 100% depth-of-discharge until capacity stabilized at a minimum of 98% of the manufacturers' stated capacity. The curves are generated by discharging each battery from full charge to 10.20 volts (1.70 volts per cell) at each of four fixed rates (c/400, c/200, c/150 and c/100) and recharging at the same rate. Voltage measurements are made throughout each cycle and the state-of-charge is determined from the ampours discharged. For example, if the capacity at the c/100 rate was 100Ah, the voltage after 50Ah have been discharged is the 50% state-of-charge point. Similarly, if the capacity at the c/400 rate was 112Ah, the voltage after 56Ah have been discharged is the 50% state of charge point. During charge, the percent capacity is determined by the amount of charge and the charge storage (ampere-hour) efficiency, since not all of the energy put into the battery is stored. The charge storage efficiency varies from nearly 100% when the battery is fully discharged to 0% when fully charged. This variation is not linear (figure 4-6). However, at the low changing rates used, the efficiency is quite high, averaging 98%-99% from the fully discharged to the fully charged condition. A function was developed to describe this efficiency from a comparison of computer modeled system to actual system behavior. A charge storage efficiency function of the form

$$E = 1.58 (1 - e^{-(1-C)^{0.1}})$$

where E = fraction of amperes stored
 C = state of charge/100

was adopted. It provided accurate predictions for the behavior of several pure lead and lead-calcium batteries operating without a voltage regulator in photovoltaic systems.⁽²³⁾

This charge efficiency was used to determine the percent capacity for the charge half of the I-V curves. Discharge is assumed to be 100% efficient.

Although the I-V curves generated by this procedure have certain limitations, they still provide a unique operating characteristic for a given battery that can be used as a valuable tool for predicting battery performance. More importantly, since the curves were derived under the same set of conditions, comparisons between battery types can be made. The significant variable in figures 5-1, 5-2, and 5-3 is grid construction: pure lead, lead-antimony, or lead-calcium. As can be seen, between zero and 75% capacity the batteries appear to be essentially the same. Above 75% capacity the I-V curves vary. Due to higher internal resistance, the pure lead and lead-calcium batteries require higher voltages to drive current through the battery above 75% capacity (figures 5-1 and 5-3) than the lead-antimony type (figure

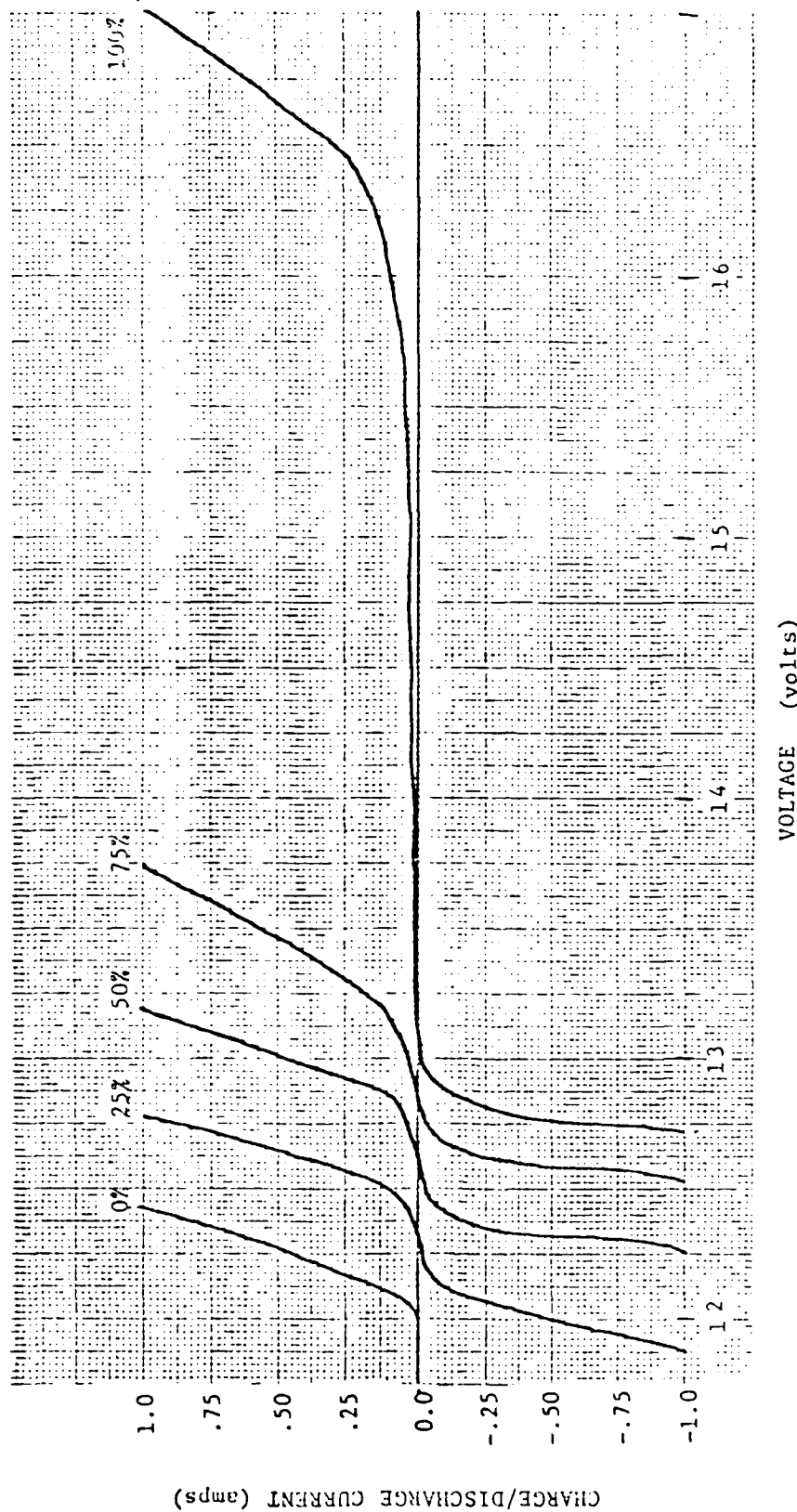


FIGURE 5-1 BATTERY I-V CURVES AT VARIOUS STATES OF CHARGE . (Pure Lead Grid)
WISCO TYPE DD-3-3, 100 Ah, Pure Lead
FULL CHARGE SPECIFIC GRAVITY 1.300
23°C

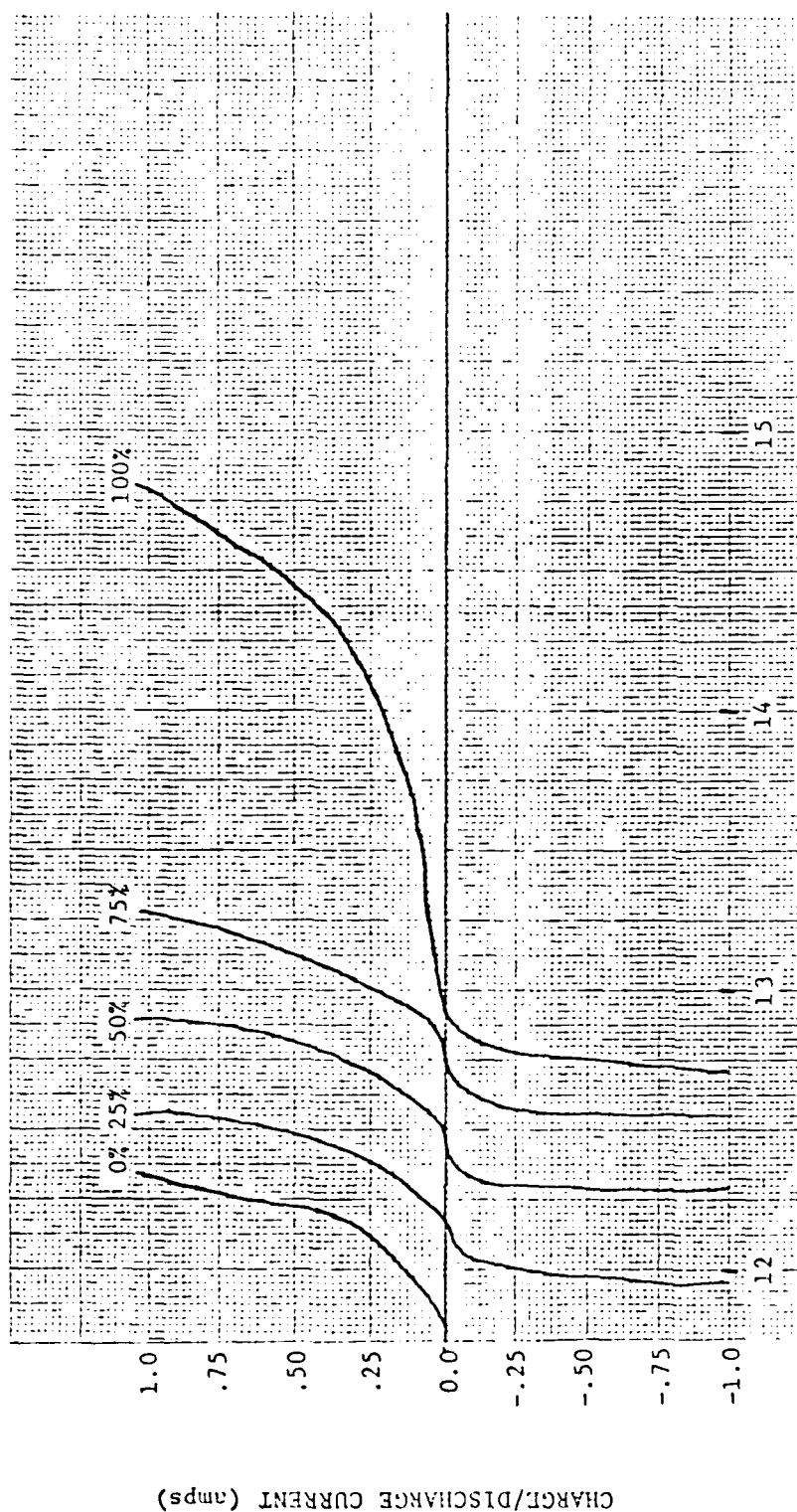


FIGURE 5-2 Battery I-V Curves at Various States of Charge (Lead-Antimony Grid)
 Mule Type 6MLG-11, 100 Ah, Lead-Antimony
 Full Charge Specific Gravity 1.285
 23°C

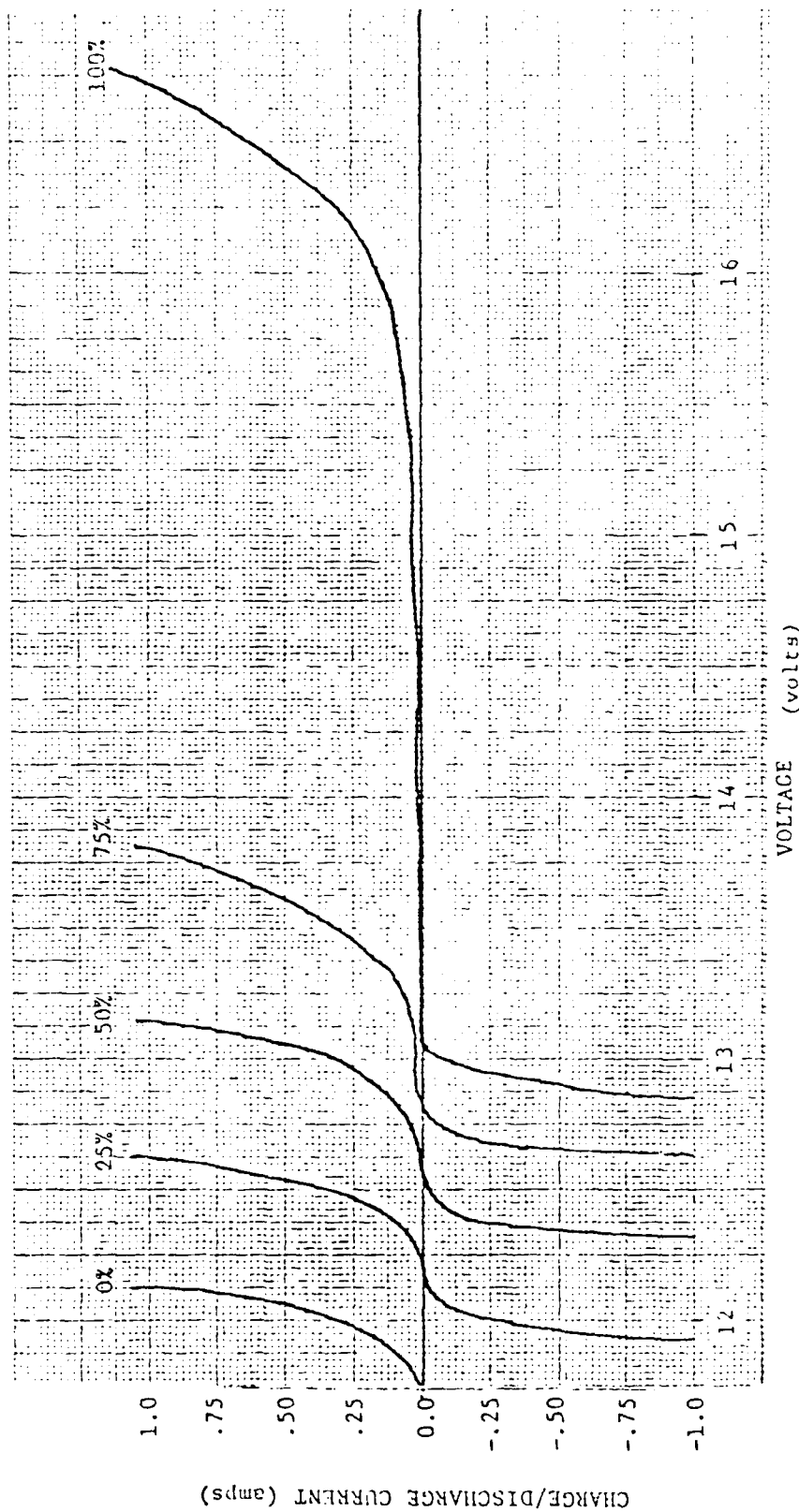


FIGURE 5-3 Battery I-V Curves at Various States of Charge (Lead-Calcium Grid)
 C&D Type 3DCP-80, 80 Ah, Lead-Calcium
 Full Charge Specific Gravity 1.300
 23°C

5-2). Therefore, when limited to a given voltage, the pure lead and lead-calcium batteries allow less overcharge current. This is important in the selection of a voltage regulator.

Limitation on the use of the I-V curves in figures 5-1, 5-2, and 5-3 includes sampling, cycling, and temperature considerations. Each set of I-V curves for a given battery were derived through the use of one battery only. While this gives a sample size of only one, the batteries were not randomly chosen. Each battery was cycled to guarantee its conformance to manufacturers data. Consequently, the curves can be considered characteristic of the generic battery type. To have derived statistically correct curves for a given general battery type was not within the scope of this effort.

It must be recognized that each data point collected on any battery is unique as batteries change slightly from one cycle to the next. This is true especially when batteries are subjected to the depth of discharge needed to derive the I-V curves. The effect is not quantifiable, but its importance is minimized by subjecting all of the batteries to the same procedure.

The I-V curves vary with temperature due to the temperature sensitivity of the battery's internal resistance. The internal resistance varies inversely with temperature. If the battery is on charge, higher charging voltages are required to overcome the increased resistance. If the battery is on discharge, the result is lower voltages for similar discharge rates. Figure 5-4 illustrates the temperature effect on two batteries at 100% capacity.

A check on the I-V curves is possible through a post hoc analysis of water usage data taken during 1978, 1979, and 1980 from the two unregulated Wisco systems that have continued to operate and the five unregulated Mule systems being used in voltage regulation testing. From the 100% capacity curves, at equal voltage regulation points, the Mule systems would be predicted to allow more overcharging of the battery when charged by a typical solar panel than the Wisco systems. As 3 ampere-hours of overcharge disassociate 1 ml of water per cell, this overcharging should increase water usage in Mule systems.

Testing the null hypothesis that there is no difference in water usage between the Mule and Wisco systems was accomplished for each year using the Student's t-test with pooled variance. Table 5-2 presents the comparisons. As can be seen, the Mule batteries used significantly more water during 1978 and 1979. For 1980, the difference in the variances of the data for each battery type was significant, thus it was necessary to use Cochran's Approximation Method as the test statistic.⁽²⁴⁾ This test did not indicate significantly more water usage even though the Mule batteries are seen to have a higher average water usage than did the Wisco batteries.

Another check on the I-V curves can be made by comparing average water usage for five Mule batteries regulated at 13.8V (10% depth-of-discharge) with five Wisco batteries regulated at 14V (10% depth-of-discharge). May 1979 and May 1980 averages for the Mule batteries were 105.8 ml and 294.8 ml. The Wisco systems did not use any water in either year.

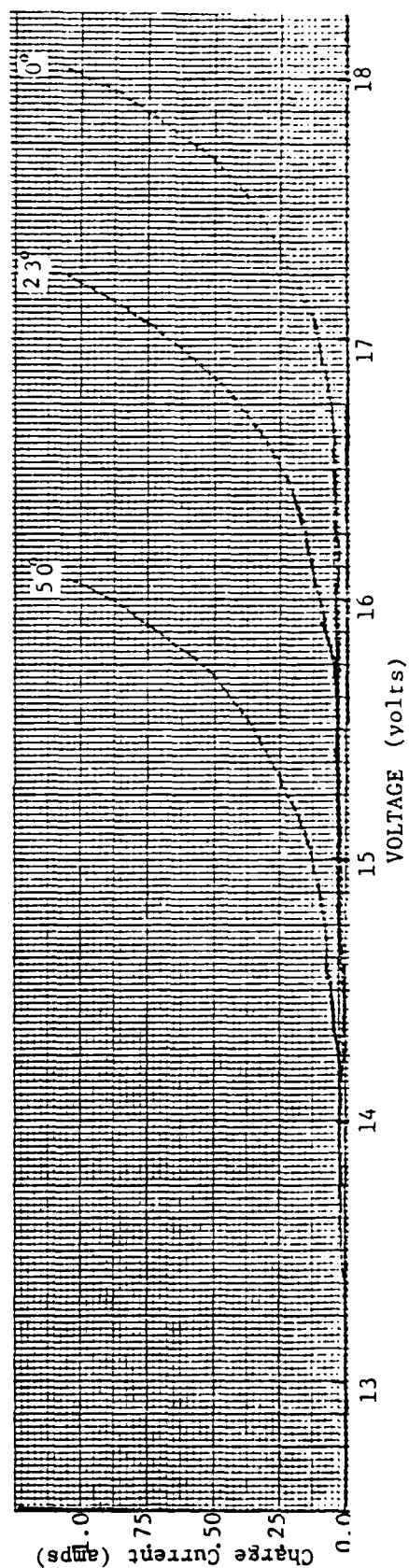
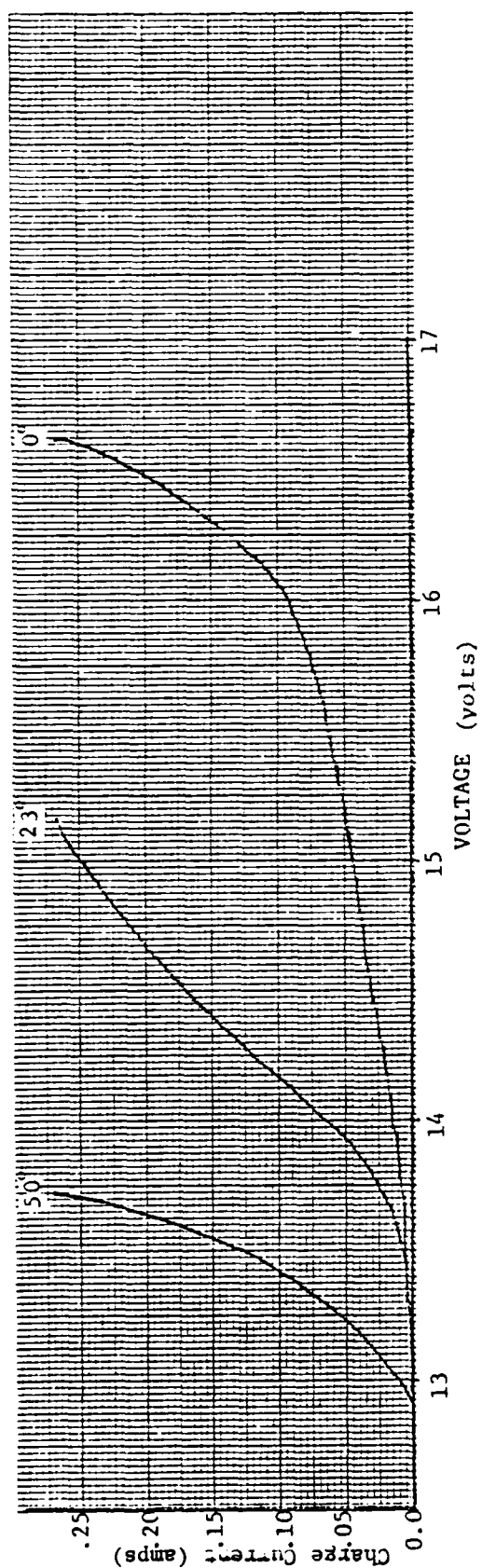


FIGURE 5-4 Variation of Voltage With Temperature ($^{\circ}\text{C}$) For a Fully Charged Battery

Taken together, there is strong evidence that the Mule batteries used significantly more water than did the Wisco batteries. The practical conclusion therefore is that the characteristics of the Wisco batteries, illustrated in the I-V curves, contributed toward significantly less water usage. The generality derived from these considerations would be that batteries with rather flat 100% state-of-charge I-V curves (such as those shown in figures 5-1 and 5-3) when placed in photovoltaic-powered systems, have inherently superior self-regulating characteristics compared to those with greater slopes (such as the one shown in figure 5-2).

TABLE 5-2

MEAN WATER USAGE (ml) FOR UNREGULATED MULE⁽⁴⁾
VERSUS UNREGULATED WISCO⁽⁵⁾ BATTERIES FOR 1978, 1979, 1980

		1976-77(3)	1978(2)	1979(2)	1980(2)
Mule Batteries	\bar{X} (mean)	1923.60	922.80	712.60	986.67
	S.D. (standard deviation)	200.05	87.89	125.79	56.6
	n (sample size)	5	5	5	3
Wisco Batteries	\bar{X} (mean)	(6)	92.51	65.51	331.00
	S.D. (standard deviation)		130.81	92.62	380.42
	n (sample size)		2	2	2
Student's t-value			10.31*	6.45*	3.20(1)
Degrees of freedom			5	5	3

* Indicates a significant difference in sample means at 95% or greater confidence level

(1) Unequal variances. No significant difference using Cochran's Approximation Method.

(2) Readings taken in May.

(3) Total of two years.

(4) Reserve electrolyte capacity = 1860 ml

(5) Reserve electrolyte capacity = 1230 ml

(6) Readings not available.

5.3 Overcharge Gassing of Electrolyte

Failure to regulate the overcharge current to a battery results in the loss of electrolyte. As previously mentioned, the generally accepted rate is one milliliter of water per 3 ampere-hours of overcharge per cell of the battery. To verify this disassociation rate applied to aids to navigation usage, an analysis was done on the water usage of five unregulated Mule MLC-11 lead-antimony batteries. Solar panel and load were sized to produce 500 ampere-hours of excess energy, as predicted by the Coast Guard R&D Center's mini-Design Integration Model computer model.⁽²⁵⁾ For 500 ampere-hours of overcharge the expected water usage should be

$$\frac{500 \text{ ampere hours}}{\text{year}} \times \frac{1 \text{ ml water}}{3 \text{ ampere-hour-cell}} \times 6 \text{ cells} = \frac{1000 \text{ ml water}}{\text{year}}$$

Table 5-2 lists the average water usage for the unregulated Mule systems. Water use in the Mule systems was measured after the first two years of operation and yearly after that. The averages suggest that the lead-antimony batteries do disassociate water close to the predicted amount. Water usage of the Wisco systems is significantly less suggesting the battery is not receiving the same amount of overcharge due to its better charging characteristics.

5.4 Battery Grid Thickness and Life

In solar photovoltaic applications, it appears that the thickness of the positive plates of batteries is a factor in life expectancy. In the exploratory testing, the thick plate (0.62 inches) pure-lead Wisco batteries had much longer lifetimes of usage (five times) than the thin plate lead calcium (0.11 inches) Globe batteries and thin-plate (0.06 inch) lead-calcium Gates batteries. In other testing, three years of use have been obtained with C&O lead calcium batteries with thick positive grids (0.266 in). It is believed that a sulfate barrier forms around the positive grid of the thin grid lead-calcium batteries causing a severe capacity loss. This behavior was first reported by Tudor, Weistuch, and Davang.⁽²⁶⁾ They observed that lead-calcium batteries with grids of thickness (0.093 inch) were vulnerable to sulfate barrier formation while batteries with grids of 0.25 inches or greater were not. Batteries in our application appear to be vulnerable to sulfate barrier formation; consequently, a positive grid thickness greater than 0.25 inches should be specified for procurement.

6.0 VOLTAGE REGULATION TESTING

Previously described in section 5.1, the fifteen systems using the lead-antimony batteries constitute another distinct phase in the overall examination of batteries in solar photovoltaic systems. This avenue of inquiry sought to measure voltage regulator effectiveness using water usage and specific gravity as dependent variables and level of voltage regulation (i.e., 13.1V, 13.8V, and unregulated) as the independent variables for each dependent variable. Water usage provides a measure of the effectiveness of voltage regulation in reducing overcharge of the battery while specific gravity gives measure of the state-of-charge.

All 15 of the systems have loads of standard 0.55A lamps and changers with two 6-volt, 100 Ah Mule Model 6MLG-11 liquid, lead-acid batteries as the energy source. Maximum solar array charge current is about 0.55-0.58A. The array-load combination used was predicted to have a 10% DOD (for unregulated systems) at the worst time of the year and was designed to produce about 500 Ah of excess energy per year; these conditions were imposed to accentuate the differences in voltage regulation provided by the 13.1V \pm 5%, 50-watt and 13.8V \pm 5%, 50-watt zener diodes used. There were five systems at each of the three levels of voltage regulation at the onset of the experimentation in August and September 1975. The arrays are all horizontally mounted at latitude 41 $^{\circ}$ N; array losses due to "dirt" and other accumulations are assumed to average 5-10%.

Data collection from the 12 operating systems continues at the present time. During April 1977, one system failed due to a cracked battery case; during the winter of 1979, another system failed for the same reason. Although the cause of these failures is unknown, the freezing of the electrolyte due to a low specific gravity from undercharging is a possible explanation. The third system failed due to a solar panel failure. The battery had been discharged to such an extent that efforts to recharge it were futile.

6.1 Method of Analysis

Data analysis was accomplished through the use of standard, fixed-effect analysis of variance (ANOVA) procedures. In particular, a one-way ANOVA was run for each attribute for the three levels of voltage regulation using the software package supplied with the Center's Hewlett-Packard 9825A computer. The program used provides the F-statistic necessary to test if a difference between treatment effects (i.e., voltage regulation level) exists. Bartlett's test of homogeneity of variance was run to obtain the χ^2 -test statistic for the chi-square distribution for testing the assumption that the treatment variances are all equal. As indicated by the particular ANOVA results, specific comparisons between treatment means were accomplished by the method of linear contrasts. (27)

6.2 Results

6.2.1 Water Usage

Water usage data was first taken during April 1977, thence during May for each succeeding year. For each yearly reading, the mean amount of water used (ml) for each level of voltage regulation is shown in table 6-1

along with the F-value of the one-way ANOVA performed. All F-values were significant at the 95% confidence level, or better, requiring the examination of differences in treatment means to determine effects. Table 6-2 shows the individual t-values for each comparison between treatment means for each year. Examination of this table reveals that water usage in unregulated systems was significantly greater than that of systems regulated at either 13.1V or 13.8V. In 1980, the amount used in 13.8V regulated systems was significantly more than the amount used in 13.1V regulated systems. This data verifies that water useage is a function of voltage regulation point.

TABLE 6-1
MEAN WATER USAGE (ML/BATTERY) FOR MULE BATTERIES⁽¹⁾, 1977-1980

YEAR	ATTRIBUTE MEANS ⁽²⁾			F-VALUE
	13.1V	13.8V	Unreg	
1977	160.25 (n=4)	288.20 (n=5)	1000.80 (n=5)	62.11* (df=2,11)
1978	209.25 (n=4)	223.40 (n=5)	922.80 (n=5)	160.87* (df=2,11)
1979	48.00 (n=4)	105.80 (n=5)	714.60 (n=5)	55.93* (df=2,11)
1980	99.75 (n=4)	294.80 (n=5)	986.67 (n=3)	50.44* (df=2,9)

* Denotes significance at 95% or greater confidence level

(1) Reserve Electrolyte Capacity = 1860 ml

(2) Individual cell n's indicate the number of usable replications.

Pooled standard deviation = 105.53 ml

TABLE 6-2

COMPARISON OF WATER USAGE MEANS FOR MULE BATTERIES, 1977-1980

YEAR	COMPARISON ⁽¹⁾		
	13.1V TO 13.8V	13.1V TO UNREG	13.8V TO UNREG
1977 ⁽²⁾	1.53 (df=11)	10.03* (df=11)	9.02* (df=11)
1978	0.30 (df=11)	15.08* (df=11)	15.68* (df=11)
1979	0.80 (df=11)	9.21* (df=11)	8.92* (df=11)
1980	2.43* (df=9)	9.69* (df=9)	7.91* (df=9)

* Denotes a significant difference in the sample means at the 95% or greater confidence level.

(1) Degrees of freedom (df) associated with individual t-values derived from residual mean square in accordance with method of linear contrasts.

(2) For 1977 data, Bartlett's test for homogeneity of variance was significant, therefore, Cochran's Approximation Method was used to determine significance of the t-value.

6.2.2 Specific Gravity

Specific gravity data was first taken during February 1976, thence during each succeeding February, except for 1979 when the readings were taken during March. For each year, the mean specific gravity reading for each level of voltage regulation is shown in table 6-3 as well as the F-value of the one-way ANOVA. As with the water usage ANOVAs, all F-values were significant at the 95% confidence level, or better. Table 6-4 shows the individual t-values for each comparison between treatment means for each year. These results are quite clear: mean specific gravity increases significantly with each succeeding higher level of voltage regulation. As specific gravity indicates the state-of-charge of the battery, the lower zener diode voltages are having the effect of rejecting energy that could be stored in the battery.

Although state-of-charge versus specific gravity curves are not available for Mule batteries, a specific gravity of 1.17 corresponds to approximately 25% state-of-charge and a specific gravity of 1.27 corresponds to approximately 85% state-of-charge. For the 100Ah Mule, the difference in specific gravities between 13.1V and unregulated systems represents 60Ah of lost energy.

TABLE 6-3
MEAN SPECIFIC GRAVITY READINGS FOR MULE BATTERIES, 1976-1980

YEAR	ATTRIBUTE MEANS ⁽¹⁾			F-VALUE
	13.1V	13.8V	Unreg	
1976	1.179 (n=5)	1.238 (n=5)	1.270 (n=5)	19.37* (df=2,12)
1977	1.173 (n=5)	1.235 (n=5)	1.270 (n=5)	62.99* (df=2,12)
1978	1.173 (n=5)	1.234 (n=5)	1.264 (n=5)	70.17* (df=2,12)
1979	1.202 (n=4)	1.259 (n=5)	1.289 (n=5)	46.53* (df=2,11)
1980	1.162 (n=4)	1.202 (n=5)	1.263 (n=3)	26.00* (df=2,9)

* Denotes significance at the 95% or greater confidence level.

(1) Individual cell n's indicate the number of usable replications.

TABLE 6-4
COMPARISON OF SPECIFIC GRAVITY MEANS FOR MULE BATTERIES, 1976-1980

YEAR	COMPARISON ⁽¹⁾		
	13.1V TO 13.8V	13.1V TO UNREG	13.8V TO UNREG
1976	3.97* (df=12)	6.14* (df=12)	2.17* (df=12)
1977	7.08* (df=12)	11.08* (df=12)	4.00* (df=12)
1978	7.87* (df=12)	11.60* (df=12)	3.73* (df=12)
1979	6.27* (df=11)	9.58* (df=11)	3.51* (df=11)
1980 ⁽²⁾	3.24* (df=9)	7.20* (df=9)	4.55* (df=9)

* Denotes a significant difference in the sample means at the 95% or greater confidence level.

(1) Degrees of freedom (df) associated with individual t-values derived from residual mean square in accordance with method of linear contrasts.

(2) For 1980 data, Bartlett's test for homogeneity of variance was significant, therefore, Cochran's Approximation Method was used to determine significance of the t-value.

6.3 Conclusions

The voltage regulation testing verified that a trade-off exists at any regulation point between water usage and the state-of-charge of the battery in winter. The trade-off in voltage regulation point has ramifications that affect the entire aids to navigation system. A decision to allow high water usage due to a high voltage regulation point increases the recurring costs of the system because of the need for more numerous maintenance visits to replace water. An alternate approach would be to design a battery with a large reserve of electrolyte. A decision to regulate at low voltage adversely affects battery life by cycling the battery to greater depths of discharge. In cold climates, an immediate system outage due to electrolyte freezing is possible. The effects of a lower voltage regulation point can be overcome by increasing the solar panel size, which increases the daily energy input reducing the depth of discharge in winter and raising the specific gravity, but increasing the initial costs of the system.

In order to further quantify the parameters of the voltage regulation trade-off, the life expectancy testing phase was initiated.

6.4 Lead-Antimony Batteries

Although the lead-antimony grid batteries were not considered to be the optimum choice for a solar photovoltaic energy system, the voltage regulation testing demonstrated that with some maintenance, they are capable of operating at least five years in aids to navigation usage. The high water use observed in the unregulated systems argues for mandatory voltage regulation of lead-antimony batteries or the construction of batteries with greatly expanded reserve electrolyte capacity. The low specific gravity readings in winter of the 13.1 volt regulated systems indicates that the voltage regulation point of 13.1V was too low. The failure of one system due to a cracked battery case which occurred in the winter also indicates undercharging. A regulator, with better temperature characteristics than a zener diode, is probably needed with lead-antimony batteries.

7.0 LIFE EXPECTANCY TESTING

The experience derived from the exploratory and voltage regulation testing phases suggested the need for a means to predict the life expectancy of batteries in solar photovoltaic energy applications. Accordingly, in the summer of 1978, a project was initiated. The stated objectives were first to define the effects of overcharge (i.e., voltage regulator level) and depth-of-discharge on yearly battery water replenishment and battery life. The second objective was to determine what special benefits, if any, a temperature-controlled voltage regulator might offer a solar energy battery storage system.

7.1 Experimental Design

To examine the effects of overcharge and depth-of-discharge (DOD), a standard, two-level, factorial experiment was conducted following the procedures set forth in DuPont's Strategy of Experimentation. Response surface curvature was gauged by employing a center point in the design.⁽²⁸⁾ A total of 31 systems were assembled, each was comprised of a solar array, a voltage regulator where required, a battery, and a load. The number of systems, the regulating point, and the load description were as follows:

<u>NUMBER OF SYSTEMS</u>	<u>VOLTAGE REGULATING POINT</u>	<u>LOAD DESCRIPTION</u>	<u>DOD</u>
4	14 Volts	0.55 A lamp, 10% duty cycle	10
4	Unregulated	0.55 A lamp, 10% duty cycle	10
4	14 Volts	0.77 A lamp, 10% duty cycle	50
4	Unregulated	0.77 A lamp, 10% duty cycle	50
7 (center point)	15 Volts	0.55 A lamp, 12% duty cycle	30

Commercially available solar arrays were employed. All batteries used in the basic test matrix were new Wisco Type DD-3-3, 6V, 100Ah units in a 12V, 100Ah configuration. In addition, five 80Ah C&D lead-calcium batteries were altered to match the operational factors of the center point, permitting limited comparisons between them and the Wisco pure lead batteries. Water usage and specific gravity were the dependent variables analyzed. The predicted depth-of-discharge was found by entering the load, battery capacity, and panel size into the mini-DIM computer model.

The second objective was addressed by incorporating a temperature-controlled zener diode voltage regulator (TCR) on a total of 8 additional systems as follows:

<u>NUMBER OF SYSTEMS</u>	<u>VOLTAGE REGULATING POINT</u>	<u>LOAD DESCRIPTION</u>	<u>DOD</u>
4	14 Volts (TCR)	0.55 A lamp, 10% duty cycle	10
4	14 Volts (TCR)	0.77 A lamp, 10% duty cycle	10

The TCR incorporates a thermal switch in series with the zener diode regulator. The switch opens the circuit to the zener diode at $2 \pm 2^\circ\text{C}$ and closes at $10 \pm 2^\circ\text{C}$. In Groton, Connecticut, these temperature settings ensure unregulated operation from November to March and regulated operation during the summer months.

An automatic data collection system already installed was used to monitor battery terminal voltage during charging and under load. Weekly readings were taken. The specific gravity of the center cells of all batteries was recorded to monitor the state of the batteries and to establish the actual depth-of-discharge. During May 1979 and 1980, distilled water was added to the batteries to bring the levels up to the recommended high points and the amount recorded. May was selected because during the colder months the electrolyte is artificially low due to the temperature and during late spring and summer the batteries receive a substantial amount of overcharge.

7.2 Method of Analysis

Use of Strategy of Experimentation provides the philosophic and practical elements of experimental strategies, as well as the methodology of statistical experimental design, in a "cookbook" format. In particular, the general model underlying the two-level factorial used in life expectancy testing is

$$y = b_0 + b_1X_1 + b_2X_2 + \dots + b_pX_p + b_{12}X_1X_2 + b_{13}X_1X_3 + \dots + b_{p-1,p}X_{p-1}X_p + \text{higher order interactions}$$

where y = predicted response = dependent variable
 X_p = pth factor = pth independent variable
 b_p = pth factor effect
 b_{p-1} = interaction effect for X_pX_{p-1}
 b_0 = mean

The step-by-step approach yields a prediction equation tested for response surface curvature with only the significant factors and interaction effects included (i.e., coefficients greater than variability of data). The equation can then be interpreted in terms of the independent variables used as factors. This method was used to derive prediction equations for water usage and specific gravity. Water usage data was obtained in May 1979 and 1980. Usable specific gravity data was obtained in February 1980. Specific gravity data for 1979 will not be analyzed because some batteries had an electrolyte level that was too low to obtain a valid specific gravity reading.

7.3 Results

The mean water usage for 1979 and 1980 and the mean specific gravity readings for 1980 are shown in table 7-1.

TABLE 7-1

MEAN WATER USAGE AND SPECIFIC GRAVITY FOR BATTERIES
USED IN LIFE EXPECTANCY TESTING, 1979-1980

1980 - Water Usage (ml)

		Voltage		
		14V	15V	16V
Depth-of-Discharge	10%	0		901
	30%		13.29	
	50%	2.250		242.25

1980 (Feb) - Specific Gravity

		Voltage		
		14V	15V	16V
Depth-of-Discharge	10%	1.247		1.295
	30%		1.258	
	50%	1.154		1.235

1979 - Water Usage (ml)

		Voltage		
		14V	15V	16V
Depth-of-Discharge	10%	0		158.25
	30%		0	
	50%	0		49.50

The prediction equations for water useage derived from this data are:

1979 water usage (ml):

$$y = 51.95 - 1.35 (DOD-30) + 103.87 (V-15) - 0.74 (DOD-30)(V-15)$$

1980 water usage (ml):

$$y = 286.38 - 8.21 (DOD-30) + 285.25 (V-15) - 8.26 (DOD-30)(V-15)$$

The test of the response surface indicated significant curvature for the water usage. The models are limited to the range between 10% and 50% designed depth of discharge and between 14V and 16V regulation voltage.

In analysis of the water use models, several comments are applicable:

- a. Variation in the mean usage between years is probably due to insolation differences. It may be possible to include insolation as a third factor in the model. A third year of data collection is needed prior to an attempt to incorporate insolation in the model. Battery age (cycles) could also affect water usage. Further data collection is needed to determine if age has a significant effect on water usage.

- b. The signs and relative magnitudes of the coefficients for main effects and interactions are consistent between years.
- c. The regulation voltage has the largest coefficient both years indicating it has the greatest effect on water usage.
- d. The significant response surface curvature indicating a non-linear response is not surprising due to the shape of the 100% state-of-charge curve for Wisco batteries (figure 5-1).

The prediction equation for the February 1980 Specific Gravity derived from the data is:

$$y = 1.230 - 0.002 (DOD-30) + 0.037 (V-15)$$

The response surface curvature was not significant for the specific gravity indicating that the data may be described by a linear model.

Several comments that are applicable to this model:

- a. A complete model for the specific gravity would have to include insolation plus a term that corrects for time of year.
- b. The interaction term is not significant for this model indicating that the voltage regulation point has the same relative effect on specific gravity independent of the designed depth-of-discharge.
- c. The voltage regulation change of 1 volt on the model is of equal magnitude with the depth-of-discharge change of 18-1/2%. In other words, the actual depth-of-discharge of the battery as measured by the specific gravity is a function of both the designed depth-of-discharge (a function of battery size, load, and panel size) and the voltage regulation point. A correction to the Coast Guard's design integration model (mini-DIM) computer model is needed to correct for the voltage regulation point. (29)
- d. Combining the mean specific gravity term (function of time of year and insolation) and the voltage regulation term and holding them constant, the model predicts that

$$\text{Specific Gravity} = \text{Constant} - 0.002 (DOD)$$

This is exactly the equation of the curve in figure 7-1 for Wisco batteries. This gives an independent verification of at least a portion of the model.

7.4 Comparison of Pure Lead and Lead Calcium Batteries

To compare the C&D lead-calcium batteries with the Wisco pure lead batteries at center point conditions, simple student's t comparisons were employed. Water usage data did not permit statistical comparisons because of too many zero entries. For specific gravity data, comparisons were possible for winter and summer conditions during 1979 and 1980.

Table 7-2 presents a comparison of specific gravity readings for C&D and Wisco batteries at the center point conditions of the basic test matrix for 1979 and 1980 under winter and summer conditions. In 1979 during both winter and summer, the Wisco batteries developed a significantly higher specific gravity than did the C&D batteries. This indicated that the Wisco batteries may be slightly more efficient in terms of ampere-hour storage. The C&D batteries for equal states of charge should show a slightly higher specific gravity than the Wisco batteries (figure 7-1).

TABLE 7-2
SPECIFIC GRAVITY FOR C&D VERSUS WISCO BATTERIES AT CENTER POINT
CONDITIONS OF BASIC TEST MATRIX

		General Climatic Conditions			
		Winter		Summer	
		1979 (20 Mar)	1980 (05 Feb)	1979 (07 Aug)	1980 (07 Jul)
C&D	\bar{x} =	1.271	1.235	1.289	1.287
	s =	0.005	0.015	0.006	0.008
	n =	5	5	5	5
Wisco	\bar{x} =	1.304	1.245	1.300	1.285
	s =	0.009	0.040	0.008	0.030
	n =	7	7	7	7
Student's t-value		7.44*	0.49	2.67*	0.14
Degrees of freedom		10	10	10	10

*Denotes significant difference in sample means at 95% or greater confidence level

For water usage, the data suggest no difference between the C&D and Wisco batteries. For 1979, no water was added to either battery type. For 1980, no water was added to the C&D batteries while a mean of 13.2 ml was added to the Wisco batteries; however, this latter value is considered suspect due to solar panel difficulties. Thus, the best statement permissible is that no difference was found for 1980.

The slightly higher ampere-hour storage efficiency of the solar photovoltaic energy system with the Wisco batteries and identical water usage can be explained when comparing the I-V curves (figures 5-1, 5-3) of the two

ELECTROLYTE
SPECIFIC GRAVITY (80°F)

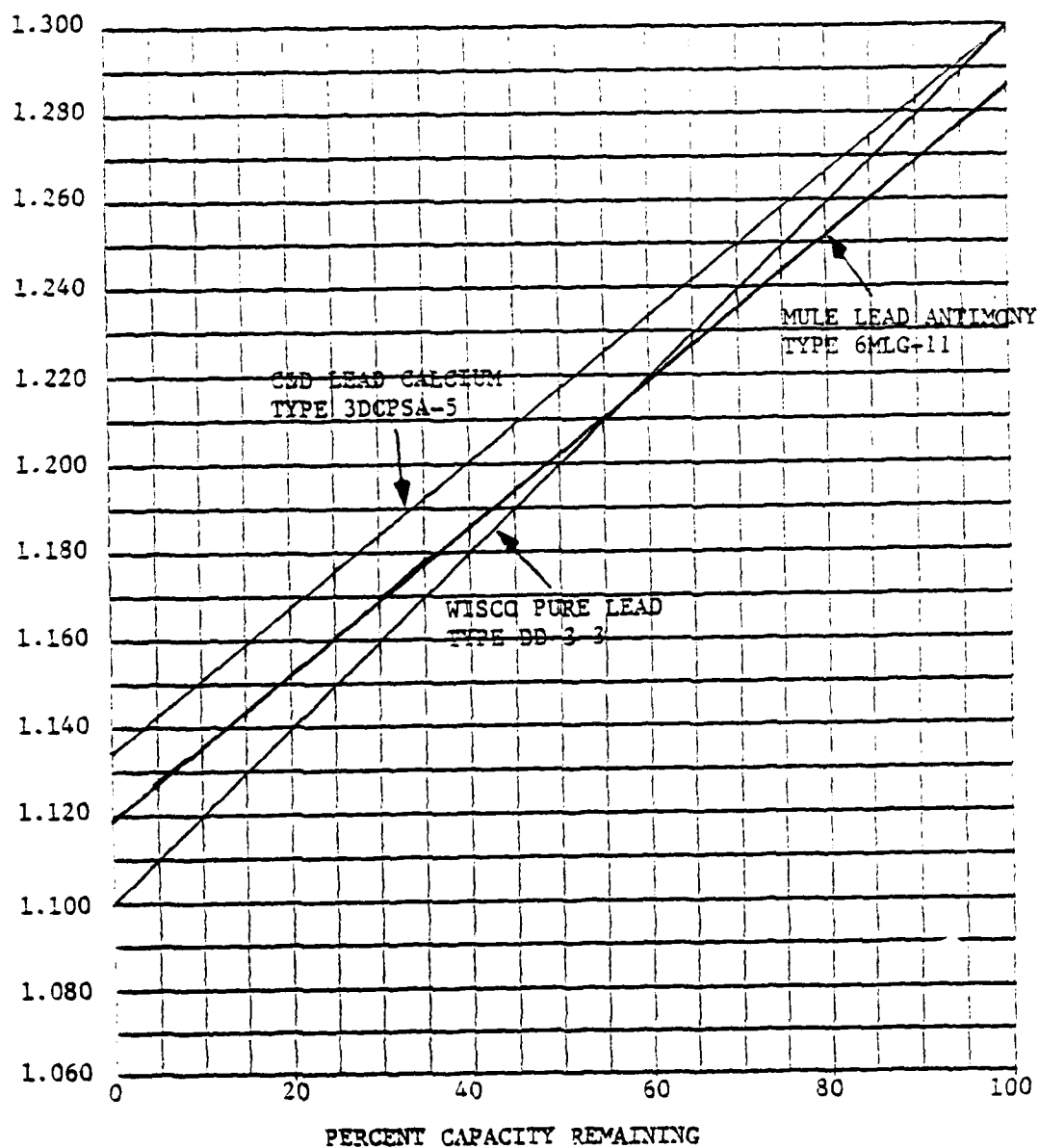


FIGURE 7-1

SPECIFIC GRAVITY VERSUS PERCENT CAPACITY REMAINING
FOR MULE, C&D, AND WISCO LEAD ACID BATTERIES

batteries. The 75% state of charge curve of the Wisco battery lies above and to the left of the 75% state of charge of the C&D battery. At any voltage when the batteries are both at 75% state of charge, the Wisco is able to accept a higher current accounting for the additional energy storage noted in the Wisco system. At 25% state of charge, the C&D appears to be capable of accepting more charge. The batteries were limited to 70% state of charge by the experimental design so the energy storage capabilities of C&D batteries at low states of charge could not be verified.

The almost identical 100% state of charge curves for both batteries explain their similar water usage.

7.5 Temperature-Controlled Regulators

A zener diode is known to change its regulation voltage directly with temperature whereas the voltage of the battery varies inversely with temperature.⁽³⁰⁾ The temperature-controlled regulator (TCR) test was designed to measure the effects of only regulating the battery during the summer to prevent water usage and not regulating in the winter to eliminate energy loss through the regulator.

To examine the effects of the temperature-controlled voltage regulators, a 2x3 standard fixed-effect ANOVA (previously described in Section 6.1) was used. Depth of discharge at two levels (10% and 50%) and voltage regulation at three levels (14V temperature-controlled, 14V, and unregulated) were the independent variables. The dependent variables were water usage and specific gravity. As before, water usage data was available for 1979 and 1980 but specific gravity data was available for 1980 only. The 10% and 50% depth-of-discharge systems at the 14V and unregulated conditions of the life expectancy test matrix were used in the 2x3 ANOVA with the 8 systems having temperature-controlled regulators.

Table 7-3 lists the mean water usage and mean winter specific gravity for the temperature-controlled regulator testing. The comparison means for both water usage and specific gravity data for 1980 for examining the effectiveness of the temperature-controlled regulator are presented in table 7-4. For both water usage and specific gravity, there was a significant depth-of-discharge/voltage regulation interaction effect. Consequently, no determination by ANOVA can be made for the significance of these main effects taken independently. With a significant interaction effect, student's t tests between cells give the maximum information that can be extracted from the data. In comparing cell means for water usage, there was significantly more water used at 10% depth-of-discharge in the unregulated condition than either of the other two conditions. This would indicate that regulating during warmer months was successful in limiting water use.

TABLE 7-3

MEAN WATER USAGE⁽¹⁾ AND MEAN SPECIFIC GRAVITY⁽²⁾
FOR TEMPERATURE-CONTROLLED REGULATOR (TCR) TESTING

		Voltage Regulation		
		TCR	14V	Unregulated
Depth-of-Discharge	10% Water (ml)	3	0	901
	Specific Gravity	1.255	1.247	1.295
	50% Water (ml)	0	2.25	242.25
	Specific Gravity	1.202	1.154	1.235

(1) Readings taken May 1980

(2) Readings taken February 1980

TABLE 7-4

COMPARISON OF MEAN WATER USAGE AND MEAN SPECIFIC GRAVITY FOR
TEMPERATURE-CONTROLLED REGULATOR TESTING

Depth of Discharge		Comparison (t-statistic)		
		TCR-14V	TCR-Unreg	14V-Unreg
10%	Water (ml)	.8455	286.09*	871.51*
	Specific Gravity	.742	3.803*	8.370*
50%	Water (ml)	1.412	1.101	1.091
	Specific Gravity	3.44*	2.648*	5.629*

* Significant difference in sample means at 95% or greater confidence level.
Degrees of freedom for all comparisons = 6.

At the 10% depth-of-discharge level, specific gravity was significantly higher in the unregulated condition than either of the other two conditions. At the 50% depth-of-discharge level, this same situation prevailed and, in addition, the specific gravity under temperature-controlled regulator conditions was significantly higher than when regulation was held to 14V. This indicates that temperature controlled regulators allowed more energy to be stored in the battery than regular zener diodes. However, unregulated operation allowed significantly more energy storage than both other systems.

In general, the temperature-controlled regulators demonstrated superior overall performance to the unregulated systems and the 14V regulated systems. The one drawback observed with this system of regulation is the reliance on a mechanical switch to control the circuit. Of the eight systems, one temperature switch has failed. This failure indicates a low reliability associated with the temperature switches that control this voltage regulation system.

8.0 DISCUSSION AND CONCLUSIONS

Reliability and effectiveness are overriding considerations in deciding on the large-scale field deployment of solar photovoltaic energy systems. They must be considered together and in systems terms rather than in terms of individual components.

Reliability is particularly difficult to establish. In the present systems, primary batteries experience a failure rate of about 21 percent according to field reports; however, in the opinion of the Minor Aids Systems Sections at Coast Guard Headquarters, the true rate is probably less than 5 percent due to the batteries themselves with the rest attributable to personnel errors, such as incorrect wiring, wrong lamp size, or rough handling, which cause premature battery failures. Thus, present power systems for 12-volt aids are probably highly reliable.

The reliability of solar photovoltaic systems properly designed and maintained in field service is largely unknown. Systems that have been field deployed for testing purposes have experienced mixed results.

While field results are not clear for various reasons, there is every indication that solar photovoltaic systems will be as reliable as primary batteries. Of course, the same factors mentioned above that contribute to premature battery failure can also be expected to adversely affect solar energy systems.

Effectiveness must be considered in terms of two dimensions: function and cost. Present energy systems are functionally effective; however, cost is a different matter. The cost of primary batteries has an upward trend and the Coast Guard must rely on only one manufacturer. It is a well-known economic phenomenon that near-monopoly conditions may experience price increases that are disproportionate to general price inflation. Technological advances continue to cause a downward trend in the cost of solar photovoltaic cells. Starting from a cost of about \$1000 per watt in the late 1950's, solar photovoltaic cells are now available at less than \$15 per watt. Manufacturers speak of costs ranging from \$0.35 to \$2.00 per watt by 1985, but this may be too optimistic for photovoltaics intended for the marine environment. There does not appear to be any equivalent great breakthrough in primary battery technology on the horizon which would improve their reliability, lower their cost, or result in easy disposal of used batteries.

Solar photovoltaic systems have proven their effectiveness sufficiently in laboratory and field testing. Their economic attractiveness combined with expected reliability and easy disposal of the used batteries provide powerful arguments in their favor.

8.1 Lead-Acid Storage Batteries

Research results have clearly shown that lead-calcium and pure lead batteries are superior to the lead-antimony type due primarily to the excessive water usage of the lead-antimony type. However, each of the three types of battery could be used in the aids to navigation system under different sets of circumstances. In the following paragraphs of this section, factors which

impact cost and reliability should be kept in mind, i.e., additional or more sophisticated components could result in lower reliability, and higher acquisition and maintenance costs.

8.1.1 Lead-Antimony Battery Usage

Testing with zener diodes demonstrated that lead-antimony batteries derived less benefit from voltage regulation than pure lead or lead calcium batteries. Under the same operating conditions, at near optimum voltage regulation points, the lead-antimony batteries used more water and dropped to greater depths-of-discharge than the pure lead batteries. To compensate for the less than optimum characteristics of lead-antimony batteries a voltage regulator more sophisticated than zener diode is needed. A sophisticated regulator with temperature compensation could probably improve the operation of lead-antimony batteries to a level that is acceptable for aids to navigation usage.

8.1.2 Lead-Calcium Battery Usage

The better charging characteristics of these batteries should allow for a much less sophisticated voltage regulator. In fixed aids to navigation which are regularly inspected and the battery is readily accessible, no voltage regulator may be necessary at all. The addition of water during the regular inspection cycle would compensate for a lack of voltage regulation. In buoy application, a voltage regulator is probably necessary to limit water usage enough to allow the system to operate six years unattended.

8.1.3 Pure-Lead Battery Usage

The charging characteristics of these batteries should also allow for an unsophisticated voltage regulator. The I-V characteristics for the Wisco pure lead battery and the C&D lead-calcium battery are so similar that the same voltage regulator and regulation point could be used for both battery types. In fixed aids to navigation the pure-lead battery probably cannot operate without a voltage regulator as the need for careful maintenance of the purity of the distilled water added to the electrolyte of the battery would complicate the refilling of the battery during regular inspection cycles.

8.1.4 Conclusions

Of these types, lead-calcium batteries are probably slightly superior, on balance. While the pure lead battery experiences lower self-discharge and better charging characteristics, it is sensitive to vibration, and shock, and requires extremely careful maintenance to avoid contamination of the electrolyte. This last consideration is important because it may be necessary during field maintenance to observe electrolyte level and measure specific gravity to determine the state of charge of the battery. Further, pure lead batteries are generally more expensive and are presently manufactured by only one company in the U.S.

8.2 Battery I-V Curves

Among the more important discoveries of the entire battery testing program is the significance and usefulness of the battery I-V curves. Their importance to systems design and battery evaluation cannot be overstressed.

Battery I-V curves allow comparisons between battery types and manufacturers and permit qualitative predictions of battery behavior within systems. The curves with lower voltage for equal charging current at 25%, 50%, and 75% capacity indicates the battery that is capable of being charged most efficiently by a solar photovoltaic charging system with or without voltage regulation (see figures 5-1, 5-2, and 5-3). The 100% capacity curve has been found to be useful in predicting overcharge, water usage, and the precision of regulation necessary for use in aids to navigation with the best characteristic being the curve with higher voltage for an equal charging current.

While their importance is evident the exact nature of the I-V curves remains something of a mystery. Consultation with various battery manufacturers suggests that they are generally unaware of the potential uses of the curves. Thus, the variables which control the I-V characteristics remain essentially unknown. Nevertheless, it seems that a given set of I-V curves must be a function of at least grid material, battery design, manufacturing quality control, and the manufacturer. The conclusion to draw from this is that battery performance is indicated by its I-V curve which in turn is sensitive to several variables.

Another point to stress in connection with I-V curves is their relationship to system performance. While grid construction may be variable, the fact that a battery may have lead-calcium or pure lead plates does not assure satisfactory operation in a system. It is the shape of the I-V curves that counts, particularly the 100% capacity curve. An I-V curve with desirable characteristics is considered to be essential prior to the introduction of any battery into the aids to navigation system.

8.3 Voltage Regulation

Some form of voltage regulation will be necessary in solar photovoltaic systems to prevent overcharging and excessive gassing. A voltage regulator can control the amount of overcharge and reduce water usage. This does not mean, however, an active voltage regulator is required. Evidence to date suggests very strongly that the charging characteristics reflected by an essentially horizontal 100% I-V curve (such as those shown in figures 5-1 and 5-3) may eliminate the need for an active voltage regulator component.

Other factors arguing in favor of elimination of an active regulator are the obvious cost savings and improved reliability. Research has also shown a voltage regulator reduces the amount of energy stored from the usual 98-99% of unregulated systems. Temperature compensation can improve the amount of energy stored in systems under active voltage regulation but even under these circumstances storage efficiency is greater in unregulated systems. Loss of storage efficiency can be compensated for by increasing the solar panel capacity which increases the cost of the system.

9.0 ADDITIONAL RESEARCH

Several additional areas of research exist that have a potential payoff in increasing the reliability, reducing the cost or simplifying the design of the solar photovoltaic energy system.

9.1 Solar Panel-Battery Self-Regulation

The addition of a voltage regulator in the charging circuit of an aids to navigation photovoltaic energy system has several drawbacks. It increases the cost of the system and introduces an additional failure point in the system potentially reducing reliability. In limiting overcharge, a voltage regulator also rejects some charge that could potentially be stored in the battery. If the water usage of the battery could be controlled by other means, the voltage regulator should be eliminated.

The results of the exploratory testing and life expectancy testing indicated that systems with pure lead and lead-calcium batteries had significant self-regulating characteristics which limited water usage. By more closely matching the panel electrical characteristics to the battery electrical characteristics, it may be possible to eliminate the voltage regulator.

Figure 8-1 illustrates how the electrical characteristics of a panel could be matched to the batteries' electrical characteristics. The battery I-V curves is for a pure lead grid battery (figure 5-1). The panel I-V curve is an actual I-V curve that has been redrawn to have an open circuit voltage of 16 volts. In practice, the open circuit voltage of the panel can be modified by changing the number of cells in series in the panel or by placing diodes in series in the charging circuit.

By reducing the panel open circuit voltage, several effects become apparent: (1) when the battery is at 50% state of charge, the panel should operate near its maximum power point. (2) When the battery is at 75% state of charge, the panel is still near its maximum power point. (3) When the battery is at 100% state of charge, the charging current of the panel is limited by the voltage of the battery to currents much less than maximum power. This is in contrast to panels presently in use which have an open circuit voltage of 19-22 volts. With presently available panels, the battery at 100% state of charge still is receiving currents near maximum power. (4) The near vertical slopes of the 50% and 75% state of charge curves and their separation allow this self-regulation to take place for any size panel provided the open circuit voltage of the panel is limited to 16 volts.

Temperature effects modify the I-V curves of both the panel and the battery and can modify the desired curve match. The panel's open circuit voltage temperature coefficient is $-2.2 \text{ mV/}^\circ\text{C}$ per cell in series. For a 33-cell panel, the coefficient is approximately $-70 \text{ mV/}^\circ\text{C}$. The temperature coefficient of the batteries at 100% state of charge is about $-45 \text{ mV/}^\circ\text{C}$ from figure 5-4. As both voltages vary inversely with temperature, although at different rates, this curve match is only slowly shifted. This is in contrast to a more rapid mismatch with zener diode regulation whose voltage characteristics varies proportionally to temperature. An additional factor is the seasonal voltage reduction of the battery as it operates at less than 100% state of charge.

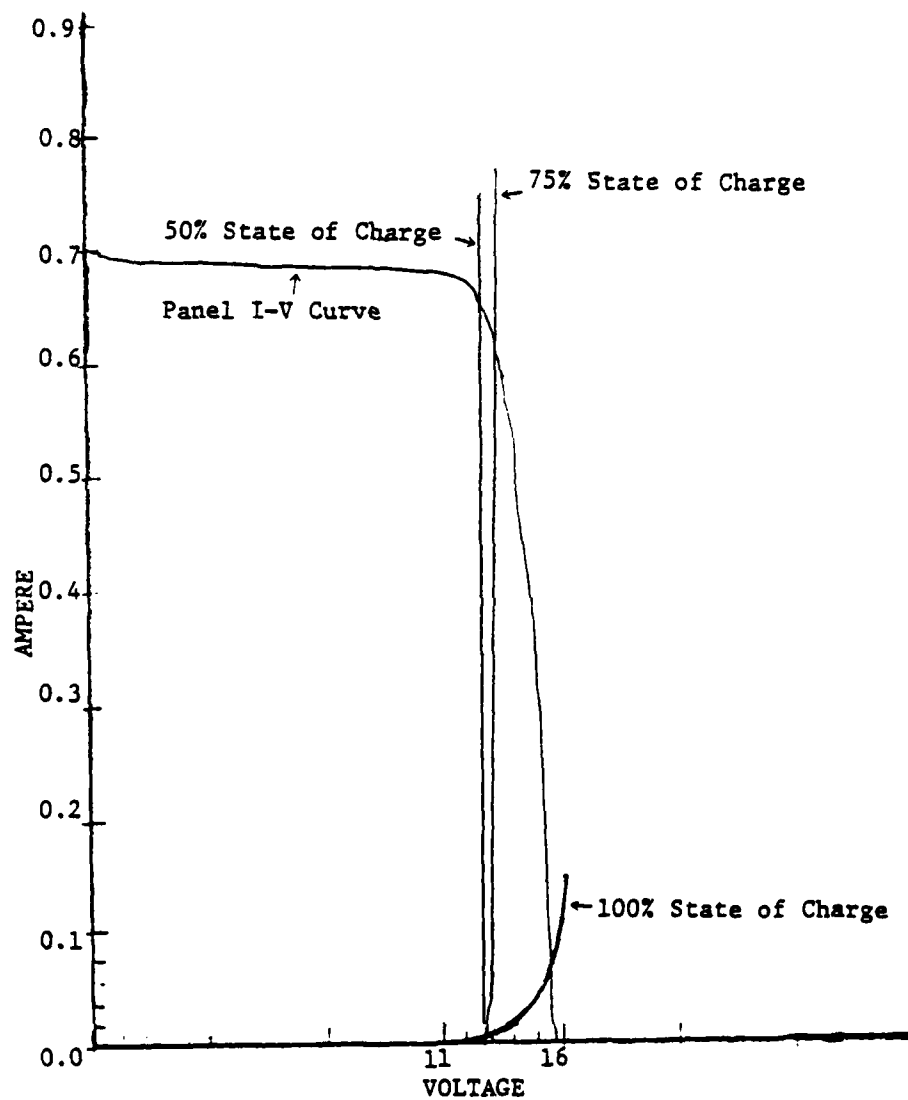


FIGURE 8-1

PURE LEAD GRID BATTERY I-V CURVES AND A HYPOTHETICAL PANEL
I-V CURVE WITH AN OPEN CIRCUIT VOLTAGE OF 16V

There are several questions concerning unregulated operation that need to be addressed in future research. They include ability of the panel to charge the battery within these close tolerances and the effect of the differences in temperature coefficient will have on water usage.

9.2 Battery I-V Curves

All battery I-V curves were based on the measurements of one sample. The sample size should be increased to verify the results and quantify the variability of the I-V curves. Solar panel-battery self-regulation depends on a low variability of the battery I-V curves.

9.3 Stratification

On the fixed aids to navigation, a potential problem with electrolyte stratification could develop. Stratification is an uneven mixing of acid and water in the electrolyte seen on stationary batteries that are receiving low charging and discharging currents. All batteries in our various test stands were mixed quarterly to prevent stratification. Further research is needed to identify whether stratification is a problem and how it can be controlled. One method of preventing stratification is to mildly gas the electrolyte.

9.4 Corrosion

Several failures of batteries during the exploratory testing and the field demonstration have been attributed to battery terminal corrosion. Terminal corrosion may have a significant adverse effect on the life of batteries on aids to navigation to the point of being the limiting factor of the life of the aids to navigation system.

Several compounds and protective techniques are used to protect battery terminals from terminal corrosion. Further research is needed to identify methods and materials applicable to the aids to navigation application.

9.5 Solar Photovoltaic Panels

The experience gained from the exploratory testing, voltage regulation testing, and the life expectancy testing shows that solar panel failures were far and away the most likely cause of battery failures in solar photovoltaic energy system operation. Continuing research is needed in solar photovoltaic panels to raise their reliability to a level near that of batteries.

10.0 AIDS TO NAVIGATION SYSTEM RECOMMENDATIONS

The experience gained in operating solar photovoltaic systems on the rooftop at the Coast Guard R&D Center lends itself to several observations and recommendations prior to the widespread deployment of solar-powered aids to navigation:

1. Any battery selected should be specified to have a positive plate thickness greater than 0.25 inches to overcome sulfation effects.
2. Any battery selected should exhibit desirable I-V curve characteristics and should be deployed with an I-V curve of its characteristics on record. The I-V curve helps predict water usage, the voltage regulation point, and the precision of voltage regulation needed. I-V curves also allow comparisons between battery types and manufacturers.
3. Lead-calcium is the battery of choice for use but either pure-lead or lead-antimony will give acceptable performance. The pure-lead battery is only hindered by its need for extra precautions to maintain the purity of the distilled water used to replace the inevitable electrolyte loss. Lead-antimony will require a sophisticated, temperature-compensated regulator or high levels of maintenance for aids to navigation usage.
4. All experience points to the solar panel as the most likely source of system failure. Extra investment in the solar panel is needed to significantly improve system reliability.
5. Battery terminal corrosion is a likely source of reduced systems reliability which will require special measures to control.
6. A system to identify failing panels will pay large benefits by reducing unplanned emergency trips to the aids and saving batteries that would have been ruined by undercharging.
7. Some form of a central battery shop will probably be needed to recharge batteries that have been allowed to discharge in the field but are not ruined. Other functions for a battery shop could include the control of the high scrap value batteries and the testing and control of solar panels.

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APPENDIX A

SUMMARY OF SALIENT ADVANTAGES AND DISADVANTAGES FOR CANDIDATE BATTERIES FOR SOLAR PHOTOVOLTAIC ENERGY SYSTEMS APPLICATION

1. Alkaline-Manganese Dioxide

Very low self-discharge. No electrolyte leakage. Good high and low temperature operation. Very high cost. Short life. Very sophisticated voltage regulator required. High overcharge sensitivity. Disposal by burial required.

2. Cadmium-Air

High energy density. Low self-discharge. Low maintenance. High cost. Short life. Unknown shelf life and safety. Still in developmental stage. Sensitive to overcharge.

3. Lead-Acid (Antimony Alloy Grid)

Very low cost. Low maintenance. Moderate life. Very good availability. Very high self-discharge. Moderately sophisticated voltage regulator required. Poor high and low temperature performance. Can be destroyed if frozen. May experience sulfation if allowed to remain in discharged state. Overcharge may produce grid corrosion. High gassing rate on overcharge.

4. Lead-Acid (Calcium Alloy Grid/Sealed)

Very low cost. Low maintenance. No electrolyte spillage. Good self-regulation. Sensitive to overcharge. May experience sulfation if allowed to remain in discharged state. Poor high and low temperature performance. Can be destroyed if frozen. Requires boost charging at 4-6 month intervals during storage. Shelf life approximately 5 times that of conventional lead-acid battery. Charge current must be limited to prevent overheating or drying out of separator material. No hazard to personnel or equipment. Has scrap value.

5. Lead-Acid (Calcium Alloy Grid/Vented)

Essentially identical to sealed battery described above only some electrolyte spillage possible.

6. Lead-Acid (Gelled Electrolyte)

Moderate life. Low self-discharge. No electrolyte spillage. No maintenance. Good shelf life. Requires boost charge at 6-12 month intervals during storage. Very high cost. Available only in low capacities. Sophisticated voltage regulator required. Poor high and low temperature performance. Can be destroyed if frozen. Reduced service life when overcharged. Rated capacity not obtained until after several deep discharges. Topping charges recommended just prior to installation. Salvage value questionable, may require disposal.

7. Lead-Acid (Pure Lead Grid/Charge Retaining)

Low cost. Long life. Low maintenance. Excellent self-regulation. Excellent charge retention. Withstands prolonged periods without re-charge. Available only in 6-volt units from one manufacturer. Sensitive to overcharge, vibration, and shock. Poor high and low temperature performance. Can be destroyed if frozen. Can spill electrolyte. Very careful maintenance required. Has scrap value.

8. Lithium-Sulfur

Low cost (expected). Still in design/developmental stage. No maintenance. High self-discharge. Short or unknown shelf and operating life. High temperature of operation. Hazardous to personnel or equipment.

9. Nickel-Cadmium (Pocket Cell/Vented or Sealed)

Very long life. Sturdy construction. Good high and low temperature operation. Low maintenance. Long storage life. Very high cost. Very sophisticated voltage regulator required. More hazardous to personnel than lead-acid. Has scrap value. Low rate charging required.

10. Nickel-Cadmium (Sealed)

Very long life. Sturdy construction. Good low temperature operation. Low maintenance. Long storage life. High self-discharge. Extremely high cost. May experience cell reversal. Requires close control of charging source. Very sophisticated voltage regulator required. Only low capacity batteries available. Unsuitable electrical characteristics for aids to navigation application. Has scrap value. More hazardous to personnel than lead-acid.

11. Nickel-Cadmium (Sintered Plate Cells/ Vented)

Very long life. Sturdy construction. Long storage life. Low self-discharge. Very sophisticated voltage regulator required. Very high cost. May experience cell reversal. High servicing requirements. Low rate charging required. Unsuitable electrical characteristics for aids to navigation application. Has scrap value.

12. Nickel-Hydrogen

Long life. Long cycle life. Insensitive to overcharge and reversal. High energy density. High cost. Stores hydrogen under pressure. High self-discharge. High scrap value. Experience outside of orbital space-craft applications very limited. Separator manufacturing allows excessive oxygen-hydrogen recombination with eventual cell degradation and/or failure. Suitable material for pressure vessel currently a problem. Not a proven technology for aids to navigation application.

13. Nickel-Iron Alkaline

Extremely long life. Rugged construction. Comparatively little maintenance, but high servicing requirements essential. Poor low temperature

performance. High self-discharge. Battery would be very heavy for aids to navigation application. Available only from foreign sources. More expensive than lead-acid except gelled electrolyte design.

14. Nickel-Zinc (Vented or sealed)

High energy density. Good performance at high rates and low temperatures. Moderately priced. High self-discharge. Very sophisticated voltage regulator required. Short storage and operational life. Low to nonexistent scrap value. Contains mercury. Disposal probably a major problem.

15. Silver Hydrogen

No maintenance. Not sensitive to under or over-charging. Still in developmental stage. High end-of-charge pressure requiring expensive pressure vessel. Probably high cost. Short or unknown shelf life.

16. Silver Oxide-Cadmium Alkaline (Vented)

Low self-discharge. Sturdy construction. High energy density. Very high cost. Special disposal handling required. Poor low temperature performance. Electrical characteristics may not be suitable for aids to navigation application.

17. Silver Oxide-Zinc Alkaline (Vented)

Low self-discharge. Sturdy construction. Superior energy density. Excellent high rate performance. Long storage life. Poor cycle life. Sensitive to over-charge. Astronomical cost. Contains mercury. Special disposal handling required. Poor low temperature operation.

18. Sodium-Sulfur

Designed to give high power and energy densities for short periods of life. Low cost (expected). Still in design/developmental stage. Would require special insulation. High temperature of operation. Very short shelf life. Hazardous to personnel or equipment. Sodium liquid burns creating a potential fire hazard.

19. Zinc-Air

Still in developmental stage. Such problems as water loss, special recharge equipment, air scrubbers, short life, and cost have deterred most investigators.

20. Zinc-Oxygen

Comments for zinc-air apply. Similar operation to zinc-air differs only in the source of oxygen and how it is handled. Has further complication of the requirement for an oxygen reservoir.

APPENDIX B

CHARACTERISTICS OF SECONDARY BATTERIES AFFECTING THEIR OPERATION IN AIDS TO NAVIGATION SOLAR PHOTOVOLTAIC ENERGY SYSTEMS

<u>Characteristic</u>	<u>Remarks</u>
Cost	Cost per unit of service life is important. Service life is affected not only by the quality of the battery but also by the life of the aid and the susceptibility of battery to vandalism, collision, etc.
Maintenance	Minimizing battery maintenance is important, unless the maintenance requirement of the battery coincides with other required servicing of the aid.
Reliability	The battery must be highly reliable in order to provide satisfactory service to the mariner.
Charge Efficiency	A battery that stores most of the energy delivered by the photovoltaic device should be rated higher than a less efficient battery. However, with the cost of photovoltaic devices expected to decrease in the future, this must be considered together with the cost of additional photovoltaic devices.
Self-Discharge	Low self-discharge is highly desirable. High self-discharge requires additional photovoltaic devices in the system. Self-discharge also affects the ability of a battery to be field installed without pre-installation booster charge (an expensive operation since a charging facility must be maintained which requires additional manpower).
Storage Life	Good shelf-keeping qualities simplifying stock management and reduce procurement problems.
Hazard	A battery that does not spill electrolyte, does not have a propensity to explode, or does not present other serious hazards to servicing personnel is at least highly desirable, and may be considered essential. Spill-proof batteries have a significant advantage.
Availability	A battery type that is readily available from several vendors, in several sizes, is preferable to one that is available only from one manufacturer, or which must be custom constructed or which uses materials that are sometimes difficult to obtain. Note, however, that greater availability may imply other uses and hence greater appeal to a would-be thief.

Size and Weight	A battery of smaller size and lower weight is easier to handle and install.
Low Temperature Performance (sub-zero)	Where freezing might occur, a battery that has decreased capacity, is damaged by too deep of a discharge, or whose life is otherwise adversely affected at low temperatures, is less desirable.
High Temperature	Where the battery may be subjected to high temperatures, the battery must not be affected adversely (e.g., accelerated electrolyte loss, or decreased capacity).
Theft	A battery which because of its general usefulness, or potential resale value, is more likely to be stolen and is less desirable than one that does not have this potential. It is, however, an unavoidable problem as a secondary battery that is suitable for the solar photovoltaic aids to navigation application, probably will also have properties which make it attractive to the would-be thief.
Regulation	Some batteries require sophisticated voltage regulators to prevent overcharge and electrolyte depletion through gassing. Sophisticated regulators are more expensive and less reliable.
Disposal	Disposal should neither present a problem nor be costly. In the U.S.A., batteries containing precious metals must be disposed of through a central office. If they contain certain hazardous chemicals (e.g., mercury), they must be disposed of at special chemical dumps. Both of these alternatives present some degree of inconvenience and expense.

